AN INVESTIGATION OF THE INFLUENCE OF WAREHOUSE LAYOUT ON STORAGE COSTS

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SUMMARY

The objective of warehouse layout is to minimize costs, i.e. to minimize the floor space required for the storage of a certain amount of merchandise (or to maximize space efficiency) and at the same time to minimize the handling times required for the storing and retrieving of the items.

The main objective of this study was to find out if there exist layouts which yield significantly better results than others and what the characteristics of these layouts are. Further objectives were to investigate the influence of other factors (i.e. stacking depth and warehouse size) upon space efficiency as well as on the optimal solution (i.e. warehouse size, frequency of handling and unit costs).

Eighteen representative warehouse layout patterns were used as a basis for the study, each representing a different type and each having about the same storage space (= 234 pallets). For these layouts the space efficiency was calculated and mathematical formulae developed which indicated the influence of the above-mentioned factors. The handling times were calculated using standard times for fork truck performance published by the Yale & Towne Manufacturing Company. It was assumed that all the merchandise is transported and stored on pallets and that all the material handling is done by fork trucks. It was found that the layout affects the space efficiency only for relatively small warehouse sizes. For the selected layouts there were two optimal solutions, both resulting in maximum space efficiency as well as in

lowest handling times. For larger sizes, the space efficiency was almost the same for all but two of the cases. The optimal solution can therefore be found by selecting the layout offering the lowest handling times. The warehouse size considerably influences the selection of the best layout and should always be taken into consideration.

The frequency of handling has an influence only on relatively large warehouses where the difference in handling times is considerable.

The unit costs, too, influence the selection of the optimal layout. A variation of either handling or space unit costs can alter the selection. Since the handling unit cost does not vary much for different situations, its influence is not as great as that of space unit costs, where the difference can be considerable depending on the location and type of warehouse.

CHAPTER I

INTRODUCTION

The techniques of plant layout represent a field that takes an important place in every Industrial Engineering curriculum. A number of books and articles have been published about this topic and it is generally recognized as being of major importance in every industrial enterprise.

On the other hand, relatively little has been written and published about warehouse layout. This may lead one to the conclusion that warehouse layout planning is not an important field and that it can easily be done by rule of thumb and by people without special knowledge. This assumption challenged the writer to select this problem as a research topic in order to investigate the field thoroughly and to find quantitative results which could answer the following questions:

1. Which type of warehouse layout results in highest efficiency and lowest costs? (Efficiency is defined as the ratio of actual (usable) storage space and total space.)

2. How do the different layout types influence material handling costs?

3. Is there a significant difference in costs between the various types of layouts, and if so, how can the optimal layout (the one resulting in lowest costs) be determined?

4. Is it possible to give a mathematical formulation to the problem by which the optimal layout can be determined?

It seems to be clear that different types of layout will result in different space utilization, but it is not clear if this difference is large enough to justify further investigation and planning. The same thing can be said about handling costs. It will require a different amount of time to store the same number of items in different warehouses, but here also, it is not obvious if this difference is significant.

The warehousing costs can be regarded as being composed of fixed and variable components. In this study only the variable costs, i.e. the direct space costs and the operating costs of the material handling equipment will be considered. It could be imagined that a layout with a large number of aisles would result in shorter handling times but also in lower space utilization. On the other hand, a small number of aisles results in greater space utilization but higher handling times. Therefore, the conclusion can be drawn that the optimal layout will be a function of space costs and handling costs.

If there is a high frequency of material movement, it is important that the layout is designed in a way to achieve the lowest access time. If the warehouse is at a location where land is expensive or where space rent is high, the main concern will be to find a layout that results in minimal space requirements. It could also be imagined that space utilization and resulting handling times are inversely proportional. This would mean that for given space costs, labor costs and frequency of handling, there exists only one optimal layout. But it could also be that there are layouts which will result in lowest costs, regardless of the given conditions. This study should answer these questions.

The assumed problem is somewhat complicated by the fact that the shape of an existing warehouse or of the land where a warehouse is to be built does not permit the adaptation of all possible layouts. It is complicated further by the fact that one side of the warehouse has to be long enough to accommodate the expected number of trucks. However, these two problems will not be investigated in this study.

The literature research revealed nothing, either in books or in periodicals, concerning the specific problem described above. A few books were helpful as references; they are given in the Bibliography.

Assumptions

In this study the following assumptions are made:

1. All material handling is done by fork trucks and all material that arrives or leaves is in unitized form.

2. The fork truck model used is a 4000 lb. capacity battery powered type. (The reason for this choice was the availability of detailed standard data and the fact that this is a model used very commonly. The standard times and other factors (aisle width) will not vary much for different fork truck types and need not be considered separately. An exception is the narrow aisle straddle type fork truck which requires considerably less aisle space, but it was not possible to get the same standard data on performance as for the selected type of fork truck.)

3. The material to be handled in the warehouse consists of

different items which must be stored so that they will always be accessible from the aisle.

4. A stacking depth of two pallets is assumed, but the influence on space utilization by using different stacking depths will be considered.

5. The stacking height was chosen to be three pallets. (Standard times for greater stacking heights were not available.)

6. A unit load of 4000 lbs or less is assumed but, as the standard data show, the load does not influence the handling time very much and can be neglected.

7. Items are not stored according to frequency of movement but rather according to some specifications (e.g. type of goods, article number, etc.).

8. The aisle width is assumed to be 12 feet.

9. A pallet size of 48" x 40" was selected, which results with the necessary clearance on both sides of the pallet in a required floor space of 48" x 48". (The assumption that this floor space is square also makes further calculations less complicated.)

10. There are no items which require the "first in first out" principle. Using this principle it would not be advantageous to store pallets along walls and the layout would require an entirely different concept.

11. In the more complicated layouts there are aisles which cross. It is obvious that at such crossings, trucks will have to slow down or stop in order to prevent accidents. However, it would hardly be possible

to take this fact into account and it is therefore assumed that the traffic will be light and that there will be devices installed which will warn the driver of other approaching vehicles.

12. The unit of measurement that is used throughout this paper for lengths is one pallet length (1 pl) = 4 feet and equally for the measurement of surface, one pallet (1 p) = 16 square feet.

CHAPTER II

THE CALCULATION OF SPACE UTILIZATION

Different Types of Layouts and Their Space Utilization

As a basis for space utilization analysis, 18 typical layouts have been developed. It is believed that every practical type of layout can be considered as being one of these or a combination of several throughout the warehouse. The purpose of this study is to find how the space utilization varies for the different types of layouts and how the handling times are influenced. Mathematical formulae for the efficiency of space utilization have been developed for the above cases and the results are represented at the end of this section in tabular and graphical form (Table 1, Figure 19).

In the examples discussed, an attempt was made to design layouts with the same usable space to make the results comparable. However, for reasons of symmetry this was not always possible.

The following notation is used throughout:

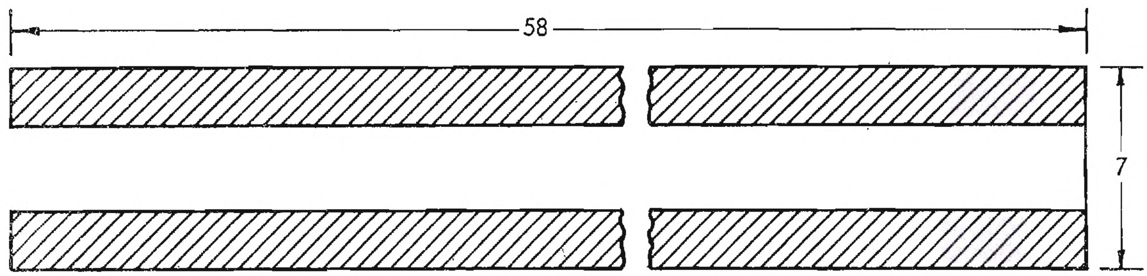
U = Usable space (actual storage space).

T = Total space (storage space + service space).

E = Storage efficiency coefficient = $\frac{U}{T}$

In the drawings each square represents a pallet. All numbers given mean either number of pallets or pallet lengths. (1 pallet = 16 square feet, 1 pallet length = 4 feet)

In these examples a stacking depth of two pallets was used.

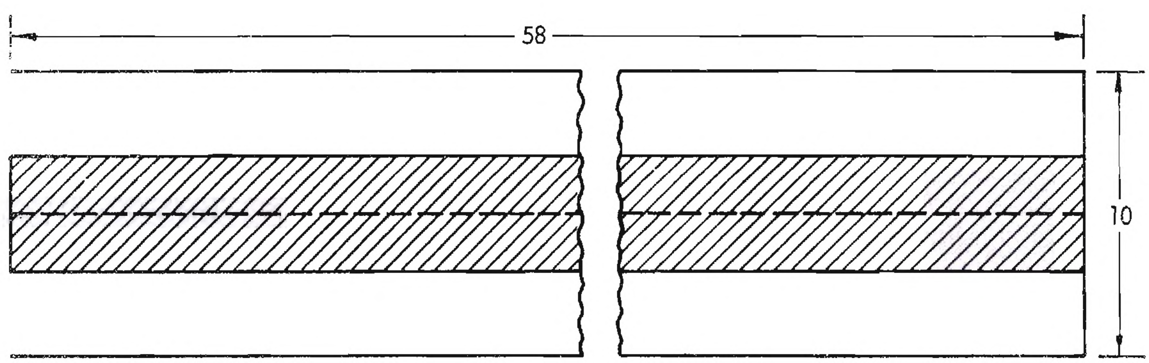


T = 406 p

U = 232 p

E = 57.2 %

Figure 1. Layout No. 1.



T = 580 p

U = 232 p

E = 40.0 %

Figure 2. Layout No. 2.

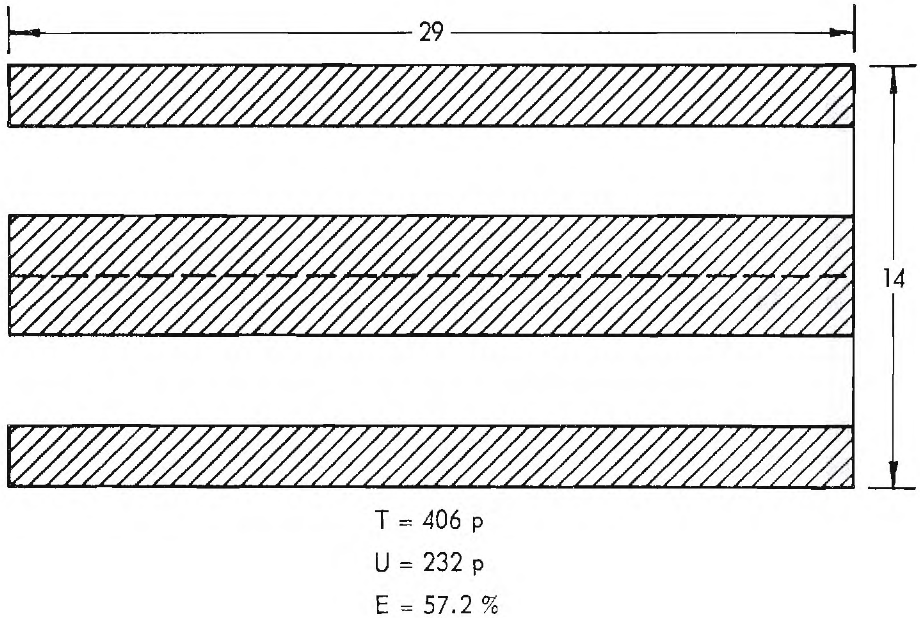


Figure 3. Layout No. 3.

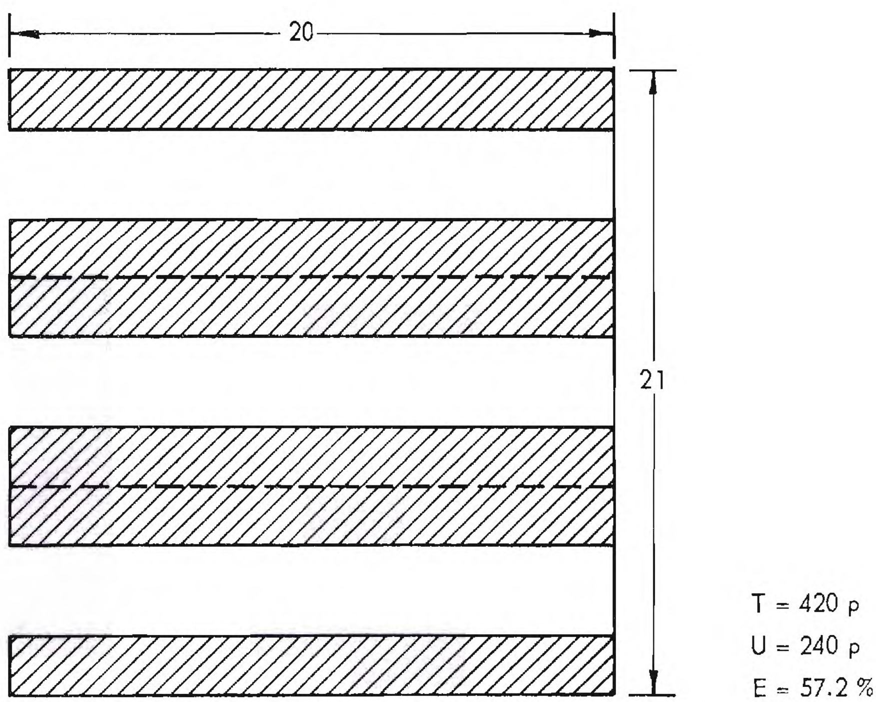


Figure 4. Layout No. 4.

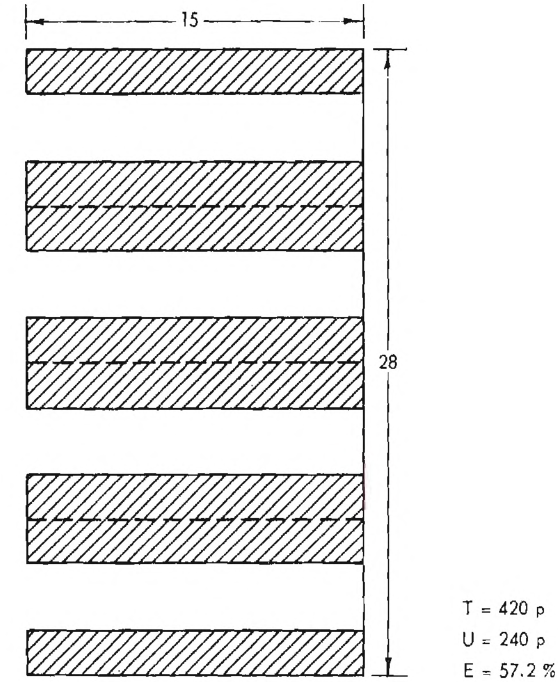


Figure 5. Layout No. 5.

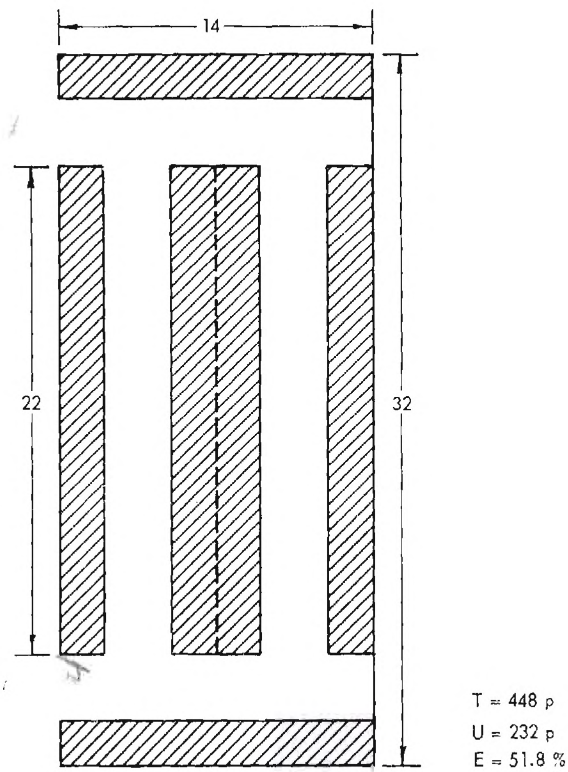


Figure 6. Layout No. 6.

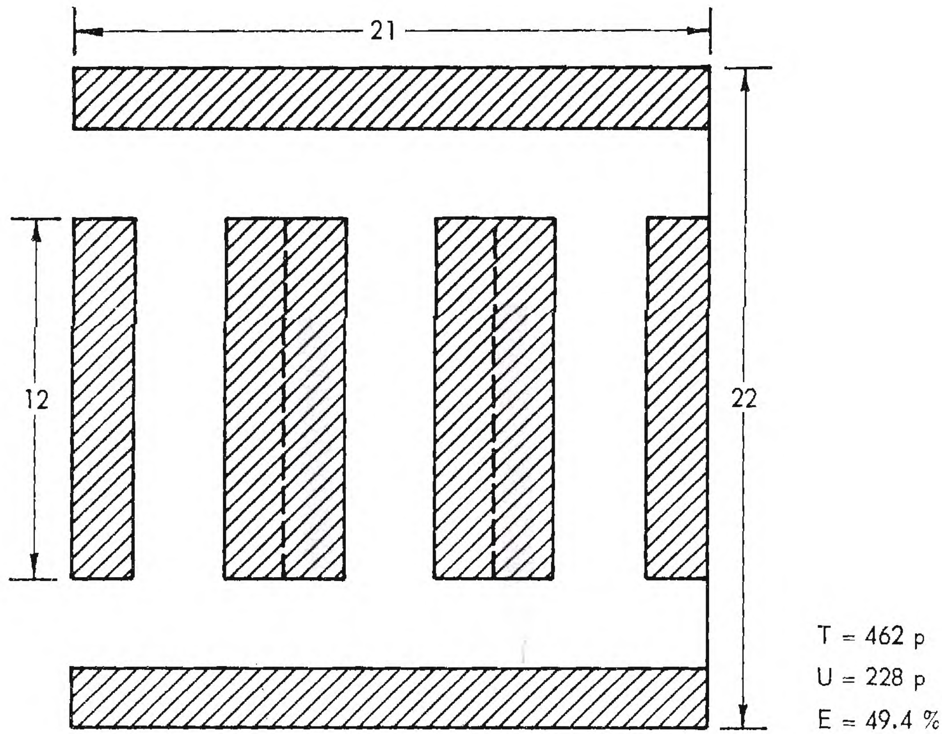


Figure 7. Layout No. 7.

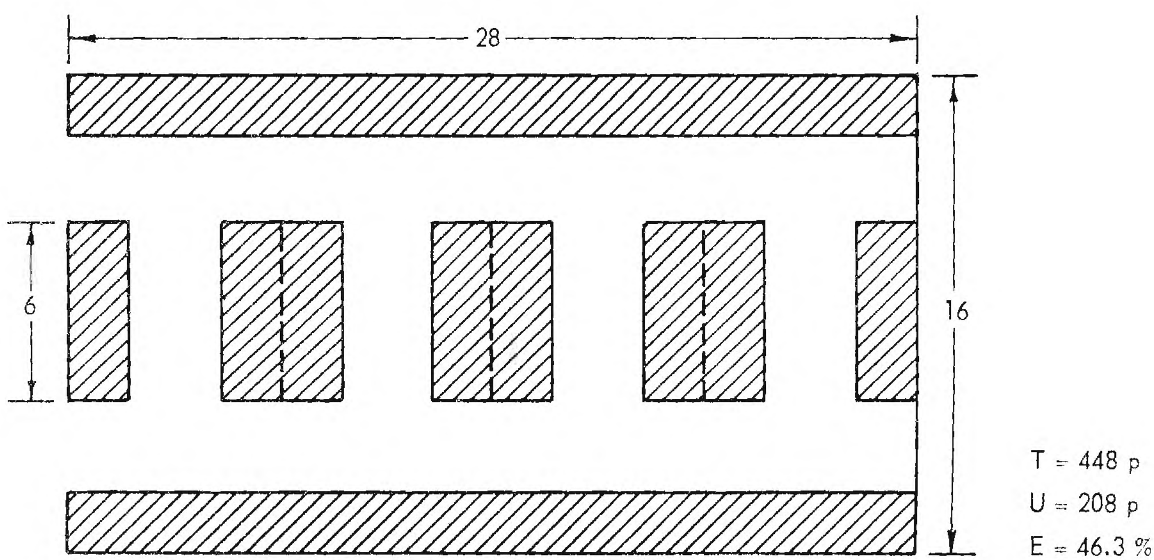


Figure 8. Layout No. 8.

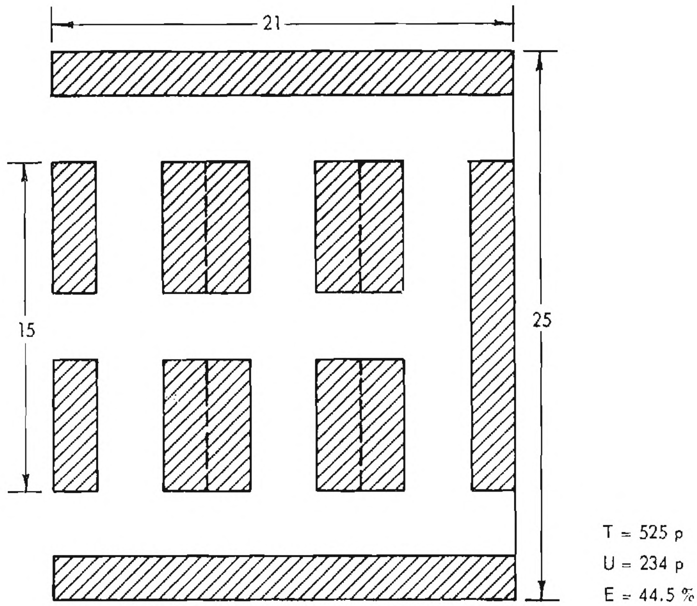


Figure 9. Layout No. 9.

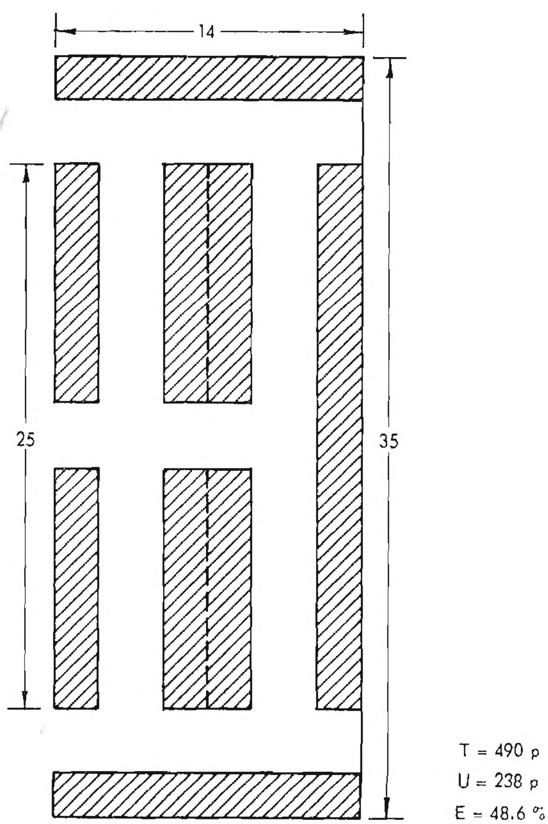


Figure 10. Layout No. 10.

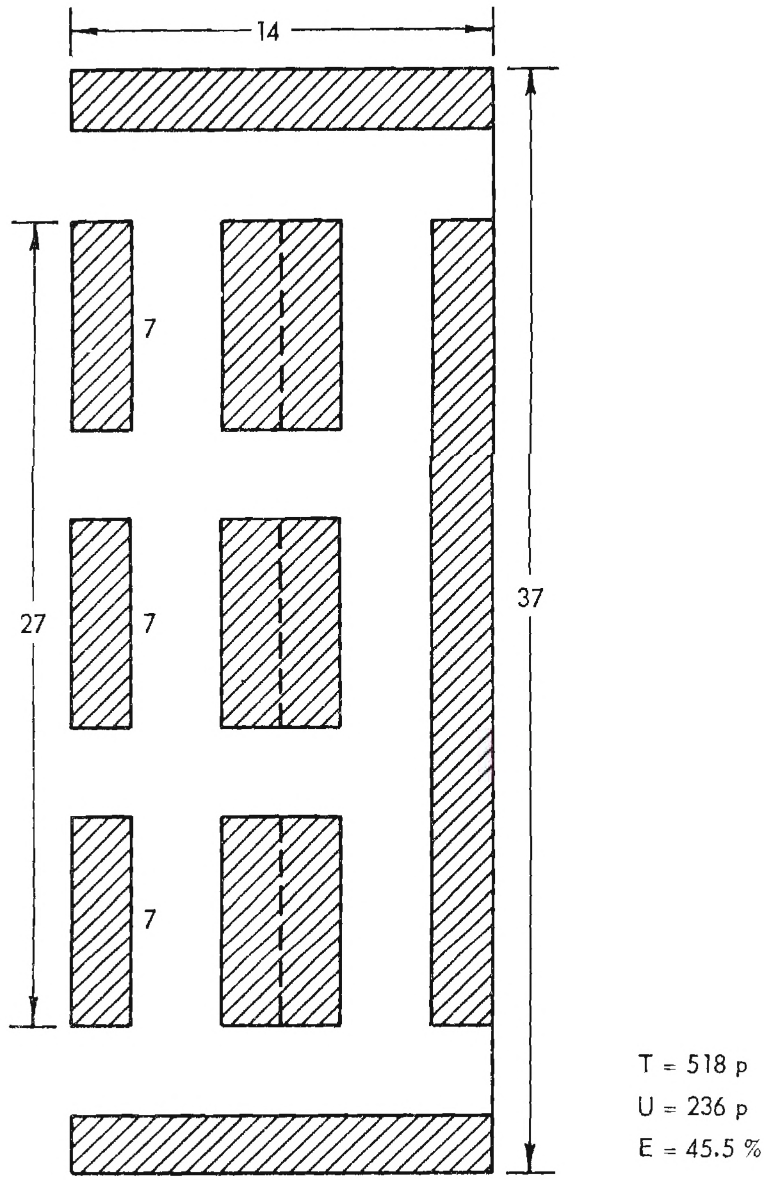


Figure 11. Layout No. 11.

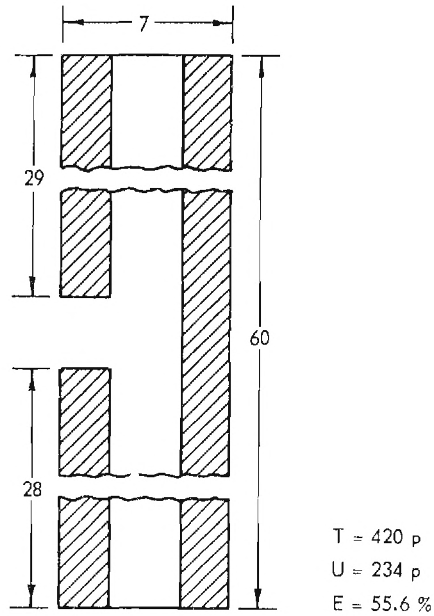


Figure 12. Layout No. 12.

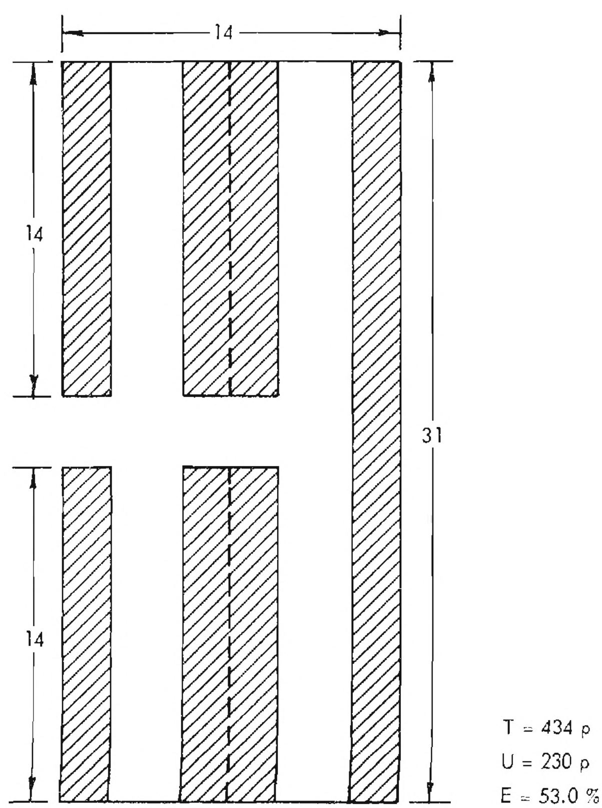


Figure 13. Layout No. 13.

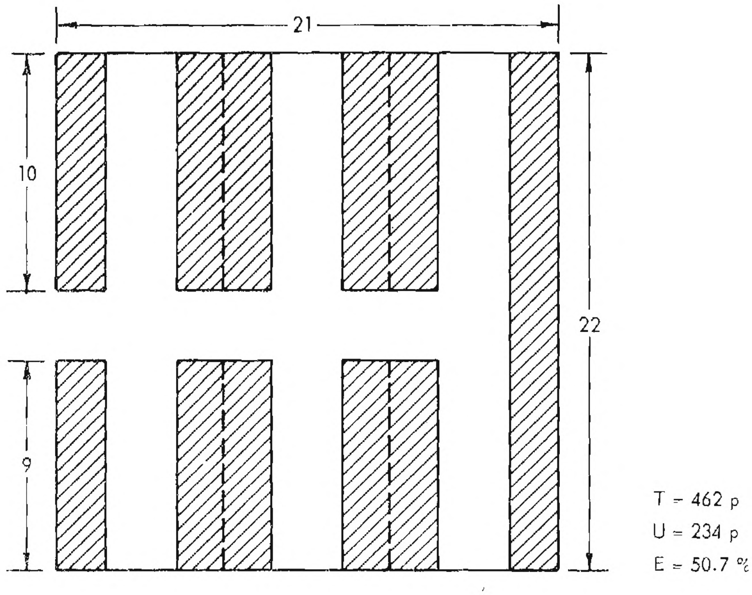


Figure 14. Layout No. 14.

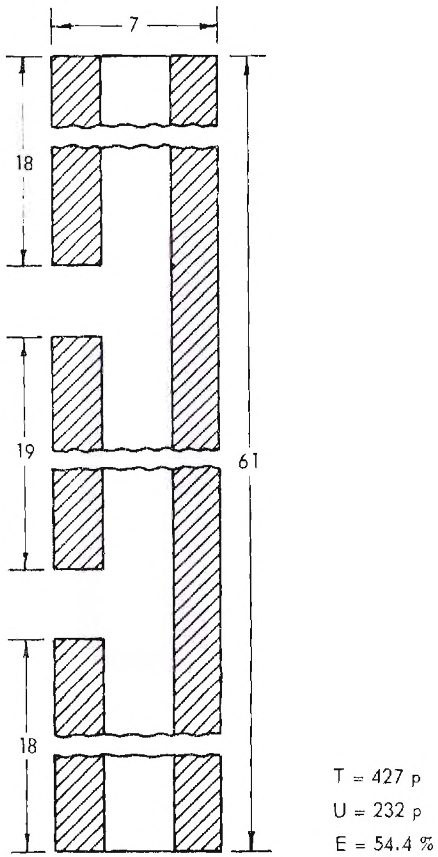


Figure 15. Layout No. 15.

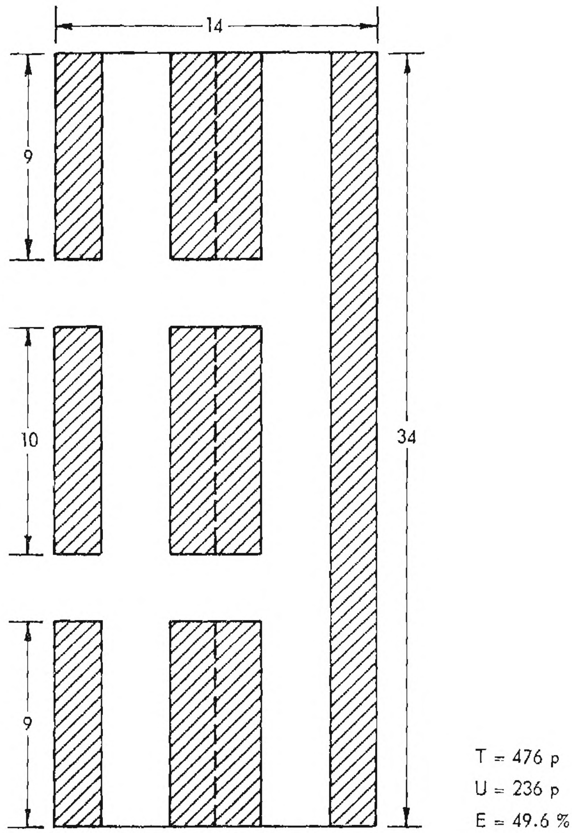


Figure 16. Layout No. 16.

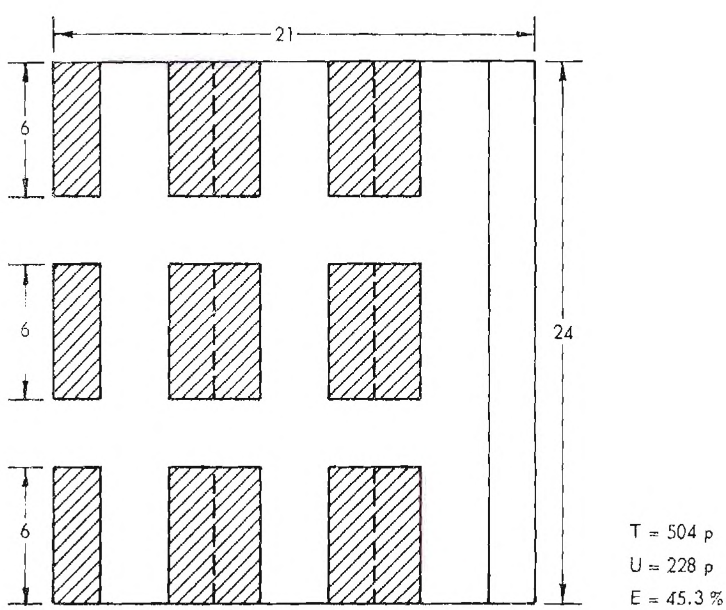
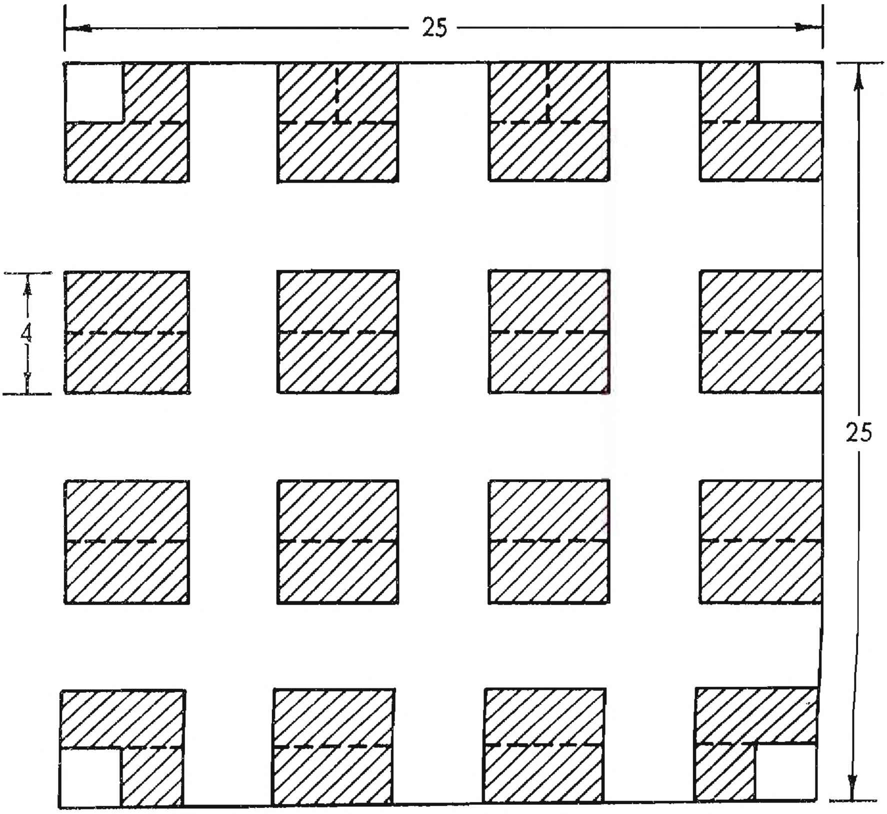


Figure 17. Layout No. 17.



$T = 625$ p

$U = 240$ p

$E - 38.5$ %

Figure 18. Layout No. 18.

Table 1. Space Efficiency of the Different Layout Types in Descending Order

Layout Number	E (%)	T (p)	U (p)	T^1 (p)	$\frac{1}{E}$
1	57.2	406	232	410	1.75
3	57.2	406	232	410	1.75
4	57.2	420	240	410	1.75
5	57.2	420	240	410	1.75
12	55.6	420	234	420	1.80
15	54.4	427	232	430	1.84
13	53.0	434	230	442	1.81
6	51.8	448	232	451	1.93
14	50.7	462	234	462	1.98
16	49.6	476	236	472	2.02
7	49.4	462	228	475	2.03
10	48.6	490	238	483	2.06
8	46.3	448	208	507	2.16
11	45.5	518	236	512	2.25
17	45.3	504	228	515	2.21
9	44.5	525	234	525	2.24
2	40.0	580	232	585	2.50
18	38.5	625	240	610	2.60

T^1 = total space based on U = 234

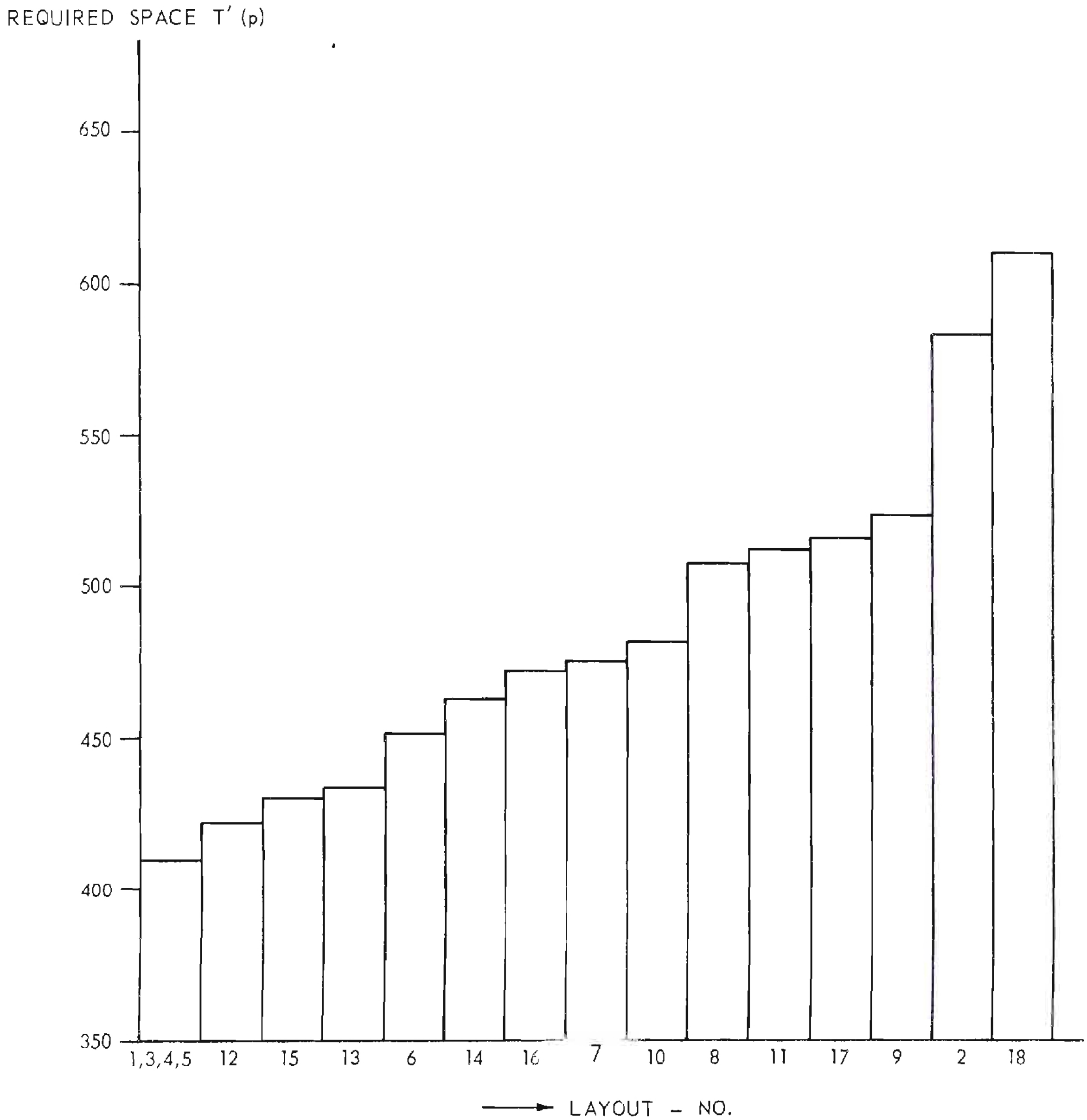


Figure 19. Total Space Required for the 18 Layouts.

The Influence of Stacking Depth on Space Utilization

Although the stacking depth is held constant and equal to two in further investigations, the influence of its variation is determined in this section because it plays an important part in space utilization. The formulas which give the relationship between stacking depth and space utilization have been developed empirically from the Figures 1-18 and are represented in Table 2.

If the given values from the corresponding layouts are introduced and the value of the stacking depth varied from one to six, the different values are obtained which are given in Table 3 and represented for a few selected layouts in Figure 20.

Table 2. Formulae for Space Efficiency as a Function of Stacking Depth

$$E = f(x) = \frac{U}{T} \, [\%]$$

Layout Number	Formula
1, 3, 4, 5	$E = \frac{2x}{2x + a}$
2	$E = \frac{2x}{2(x + a)}$
6, 7, 8	$E = \frac{(sa + 2sx)\ 2x + 2\ swx}{(w + 2a + 2x)(sa + 2sx)}$
9, 10, 11	$E = \frac{(sa + 2sx)2x + 2swx - (t - 2)(2s - 1)ax}{(w + 2a + 2x)(sa + 2sx)}$
12, 13, 14, 15, 16, 17	$E = \frac{2sxw - (2sx - x)\ at}{(2sx + sa)w}$
18	$E = \frac{4\ x^2[(s + 1)(t + 1) - 1]}{[tax + (t + 1)2x][sa + (s + 1)\ 2x]}$

x = stacking depth (p)

a = aisle width (pl)

s = number of longitudinal aisles

t = number of transversal aisles

w = length of longitudinal aisles (pl)

Table 3. Space Efficiency as a Function of Stacking Depth

$E = f(x)$ [%]

Layout	1	2	3	4	5	6
1, 3, 4, 5	40.0	56.8	66.8	73.5	77.2	80.0
2	25.0	40.0	50.0	57.2	62.6	67.0
6	37.4	51.8	61.0	66.9	71.0	74.0
7	34.0	49.4	59.2	64.4	68.8	72.0
8	31.4	46.2	55.6	61.8	66.7	70.0
9	30.4	44.7	53.3	59.0	63.4	66.5
10	33.0	48.6	57.2	63.0	67.0	70.0
11	30.3	45.0	54.0	59.5	63.5	66.6
12	41.4	55.6	64.4	70.0	73.9	76.8
13	37.0	53.0	61.3	66.6	70.2	73.0
14	35.7	50.7	58.6	62.8	67.0	69.0
15	35.4	54.4	62.3	67.3	70.8	73.4
16	34.8	49.6	56.9	61.5	64.8	67.0
17	34.1	45.3	51.8	56.8	58.9	61.0
18	23.0	38.5	39.8	57.0	62.5	66.5

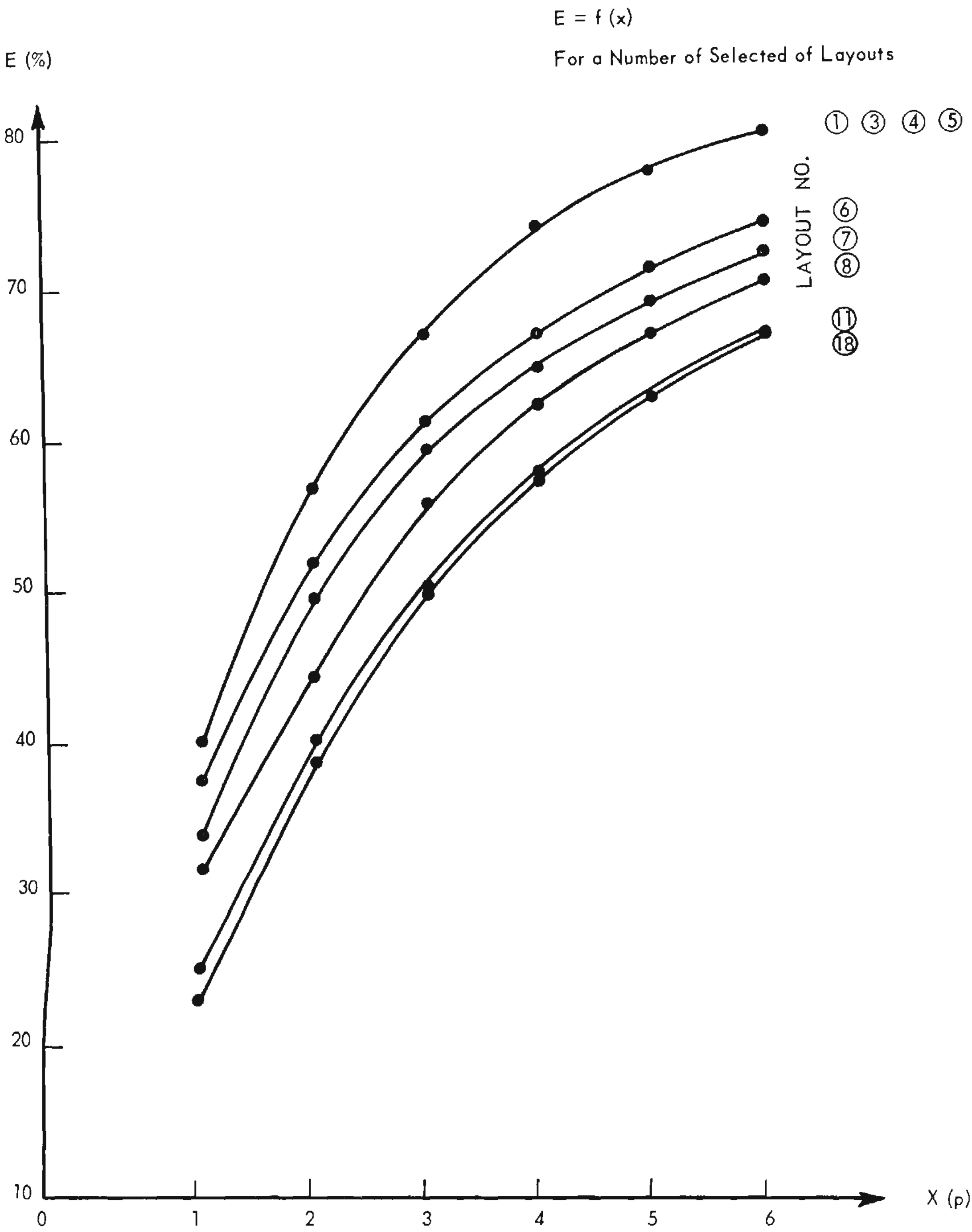


Figure 20. Space Efficiency as a Function of Stacking Depth.

The Influence of Warehouse Size on Space Utilization

There are two possibilities by which the size of a layout can be increased, namely by increasing the length or the width. The influence of these two possibilities is illustrated by the following cases:

Layouts No. 1-5: Only longitudinal expansion (length) is possible. This type of expansion does not influence the efficiency E.

Layouts No. 6-17: Transverse expansion (width) increases T and U in the same amount and the efficiency E remains constant. Longitudinal expansion has an influence on E and will be investigated in this chapter.

Layout No. 18: No extension is possible without changing character of layout. This case is therefore not investigated any further. To express the function E = f(U), the following steps have been taken: The function E = f(w) can easily be found with the aid of the formulae in Table 2 by introducing the proper values for the variables a, x and l. The variable w can also be expressed as a function of U and the combination of both formulae gives the desired function E = f(U).

The following example explains this procedure: Layout No. 6: $s = 2$, $a = 3$, $x = 2$

$$E = \frac{(sa + 2sx)2x + 2swx}{(w + 2a + 2x)(sa + 2sx)} = \frac{28 + 4w}{7w + 70}$$

The variable w can easily be expressed as a function of U by using the Figure 6:

$$w = \frac{U - 52}{8}$$

If this expression is entered into the above formulas for E, the function will be:

$$E = \frac{4U + 16}{7U + 196}$$

The formulas for $E = f(U)$ are given in Table 4. The values for the efficiency E are calculated for different sizes U and given in Table 5. A few selected values are represented graphically in Figure 21.

Table 4. Formulae for the Calculation of Space Efficiency as a Function of Size

Layout Number	E = f(U)	Layout Number	E = f(U)
1/2/3/4/5	E = constant	11	$E = \frac{4U}{7U + 420}$
6	$E = \frac{4U + 16}{7U + 196}$	12	$E = \frac{4U}{7U + 42}$
7	$E = \frac{4U}{7U + 252}$	13	$E = \frac{4U}{7U + 126}$
8	$E = \frac{4U}{7U + 336}$	14	$E = \frac{4U}{7U + 210}$
9	$E = \frac{4U}{7U + 462}$	15	$E = \frac{4U}{7U + 84}$
10	$E = \frac{4U}{7U + 294}$	16	$E = \frac{4U}{7U + 252}$
		17	$E = \frac{4U}{7U + 420}$

Table 5. Space Efficiency as a Function of Size

$$E = f(U)$$

Layout	U(p) 200	300	500	1000	2000
1/2/4/5	57.2	57.2	57.2	57.2	57.2
2	40.0	40.0	40.0	40.0	40.0
6	51.1	52.9	54.3	56.0	56.4
7	48.4	51.0	53.2	55.2	56.5
8	46.2	49.3	52.0	54.3	55.8
9*	42.9	46.8	50.6	53.5	55.4
10	46.8	50.1	52.8	55.0	55.9
11	44.0	47.8	51.0	53.8	55.2
12*	55.3	55.6	56.4	57.0	57.2
13	52.3	54.0	55.0	56.2	56.7
14	49.6	52.0	53.8	55.6	55.8
15	54.0	55.0	55.6	56.4	56.8
16	48.5	50.8	53.2	55.0	56.2
17	43.8	47.7	51.0	53.9	55.6

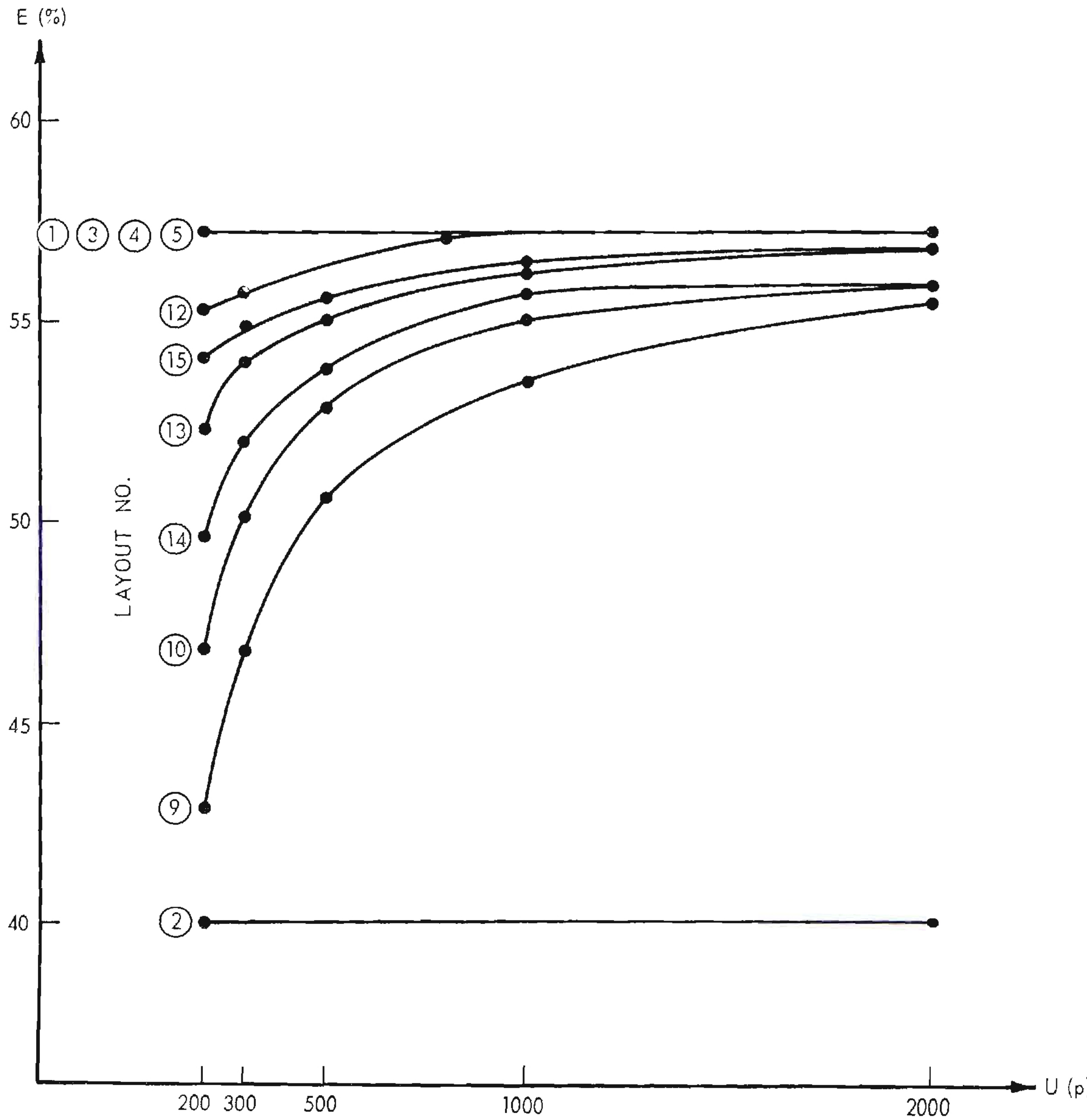


Figure 21. Space Efficiency as a Function of Size.

The Comparison of Space Requirements for the most Efficient and Least Efficient Layout

The above relationship will give an answer to the question: "What is the difference in total space between various layouts as affected by size and arrangement?"

On the basis of results given in Table 5, it appears that layout No. 12 is the most efficient and layout No. 9 is the least efficient (except No. 2). Table 6 shows the total space T as a function of usable space for these two layouts. The results are also plotted in Figure 22. For other layouts, the total space T as a function of usable space will lie between the lines A and B.

Table 6. Total Space T as a function of Usable Space U for the Most Efficient and Least Efficient Layout (No. 12 and No. 9)

	Layout Number				Difference
	12		9		
U (p)	E (%)	T (p)	E (%)	T (p)	(p)
200	55.3	362	42.9	466	104
300	55.6	537	46.8	641	104
500	56.4	886	50.6	990	104
1000	57.2	1750	53.5	1870	120
2000	57.2	3500	55.4	3650	150

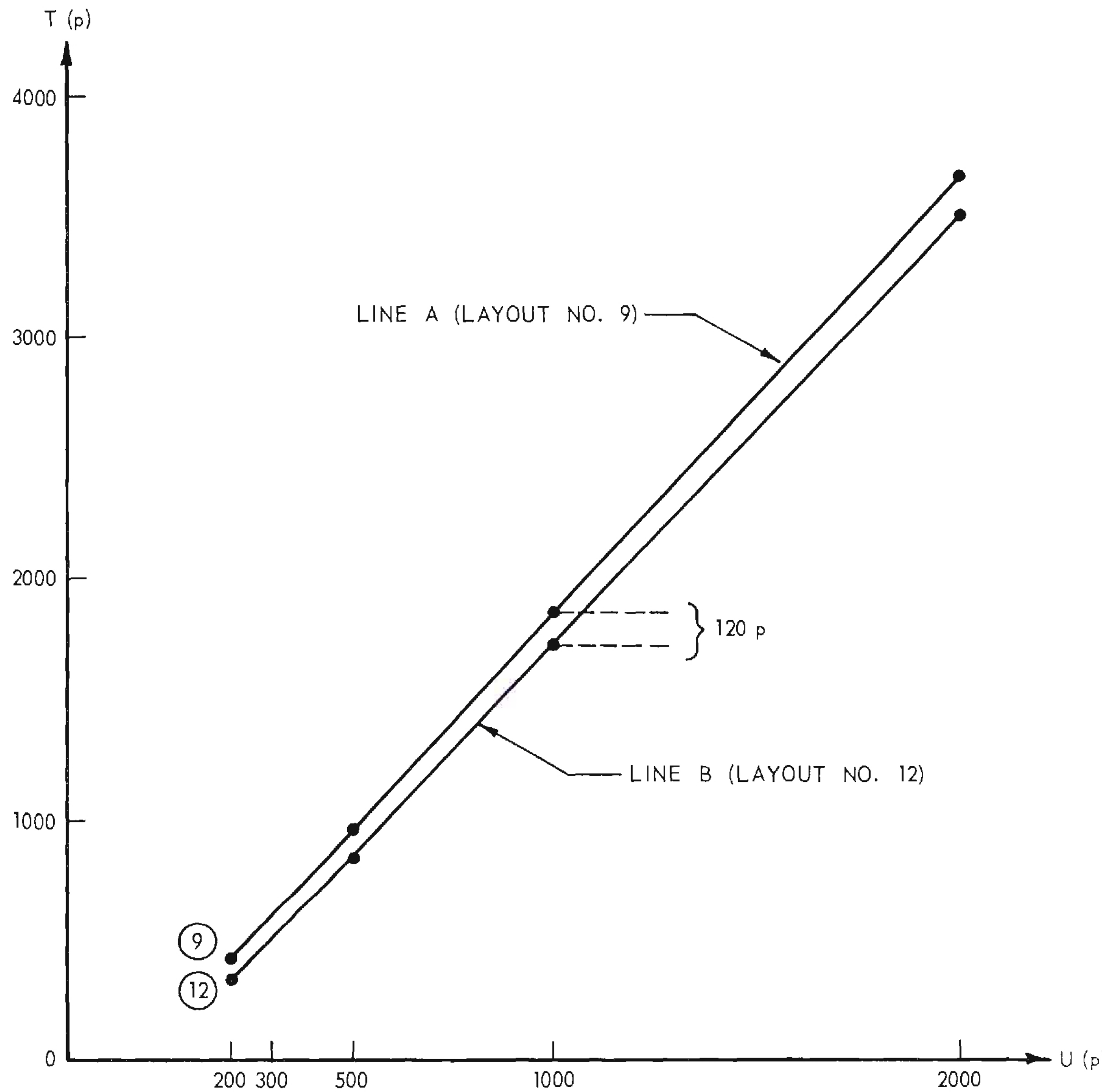


Figure 22. Total Space as a Function of Usable Space.

CHAPTER III

THE CALCULATION OF HANDLING TIMES

The basis for these calculations is an article published in Factory, April, 1954, by Robert S. Rice (see Appendix D). This article is the result of an intensive study of truck operations by a group from the University of Pennsylvania, sponsored by the Yale & Towne Manufacturing Company.

The data were collected from a large number of motion pictures taken in 18 different plants. From these, the times of all basic handling motions were calculated in order to make it possible to represent every motion as a combination of these basic motions.

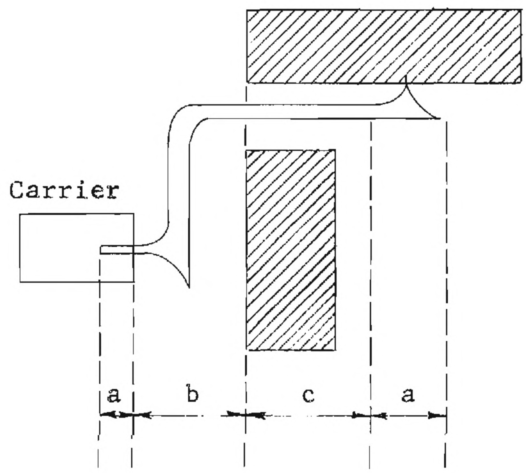
The following assumptions have been made:

1. To simplify calculations, the time used to store one unit load has been divided into three parts as the sketch below shows:

   (a) "Base Time" for pick up operation in the carrier and storage operation in the warehouse or vice-versa.

   (b) "Outside Time".* Average time used from the carrier to the "entrances" of the storage area. This time depends on the location of the parked truck at the loading ramp, which in turn depends on the number of parked trucks parked at the same time. This time, therefore, is the average of all possible situations.

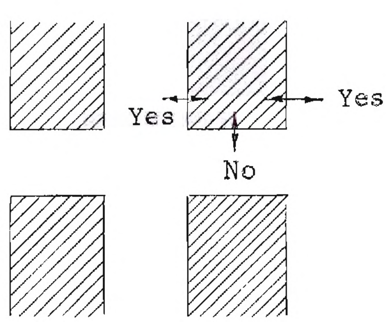
(c) "Inside Time."* Average time from the closest entrance to the place of storage.



* Actually inside and outside times are part of the same total and separated only to facilitate the calculation.

2. Since the time used for a straight run differs for a loaded and an empty truck and since the operator always drives one way loaded and one way empty, an average time of $(.0023 + .0027)/2 = .0025$ min. per ft. or .010 min. per pallet length is used.

3. The possibility of removing pallets from more than two sides of the stack as shown in the sketch below is excluded.



This assumption can be made where one or more of the following situations exists:

storage in racks.

two-way pallets.

orientation using an address system.

Since these conditions can be found in almost any warehouse, the assumption is justified.

The Calculation of the Different Time Elements

The detailed calculations of the time elements are shown in Appendix A. In this section primarily the definitions and the results are given.

1. Base Time. This element consists of the time that is needed to load one unit load inside the truck and to store it inside the warehouse or vice-versa. The time for the actual transport is not included.

The following values have been calculated in Appendix A.

Time inside truck:	.385
Time inside warehouse:	.650
Total base time:	1.035 Minutes

This base time is the same for all storage operations and can, therefore, be added to the variable times according to the different situations.

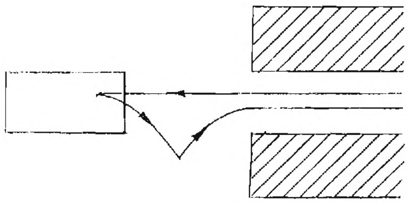
The calculations showed that the times are the same either for loading from the truck to the warehouse or from the warehouse to the carrier.

2. Average "Outside Times". The "Outside Time" is defined as the time that the fork truck spends in moving from the entrance of the warehouse into the carrier and back to the entrance. In the case where several entrances are provided the average time has been used, which is the sum of the times used for each entrance, divided by the number of entrances.

Since the assumption was made that the cargo consists of different items, the carrier cannot be located at an entrance closest to a certain type of merchandise and the average time must therefore be used.

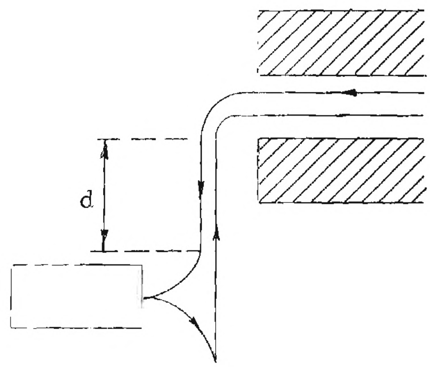
The outside time has been calculated for the following two different situations:

Case I: The truck is parked directly in front of the entrance:



Time I = .292 Minutes

Case II: The truck is not parked in front of the entrance:



Time II = .402 Minutes

Add .0025 Minutes

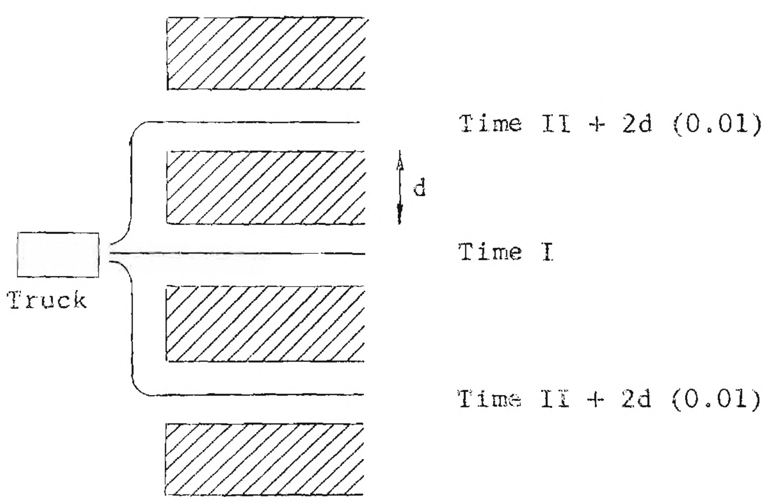
per ft. of distance d

Practical Procedure for the Calculation of the Outside Times

For all the layouts with only one entrance the outside time is merely the time of Case I from the previous page, which is equal to 0.292 min.

For layouts with two and three entrances the following equation is used, as developed from the figure given below:

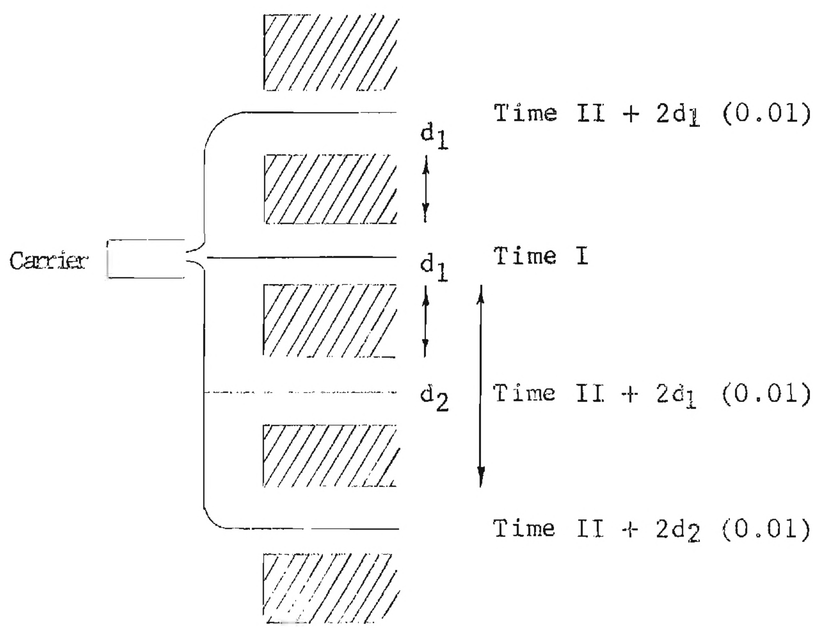
$$t = \frac{\text{Time I} + (n - 1)\{\text{Time II} + 2d(0.01)\}}{n}$$



For layouts with four entrances the following formula is used:

$$t = \frac{\text{Time I} + 3[\text{Time II} + 0.01\ (4d_1 + 2d_2)]}{4}$$

The figure below was used in its development:



The results of these calculations are shown in Table 7 and represented graphically in Figure 23.

3. Average "Inside Times." The "Inside Time" is defined as the time that the fork truck needs from the entrance of the storage area to a certain spot inside the warehouse and back to the entrance.

The calculation of these times is made in the following way: The storage area is divided into sections for which the average time can be easily calculated. These average times are then multiplied by the percentage that this section represents of the total area.

Statistically described this method would correspond to the calculation of the mean of grouped data, where the group average is the average of the trip length and the frequency of occurrence is the percentage of surface.

The detailed calculations are shown in Appendix B and the results are given in Table 7.

4. <u>Total Times</u>. The total time is the sum of base time, outside time and inside time that is needed to store one unit load. The total times are shown in Table 7 and represented graphically in Figure 23.

Table 7. Total Handling Times in Increasing Order

Layout Number	Outside Time (Minutes)	Inside Time (Minutes)	Total* Time (Minutes)
1	.292	.580	1.908
2	.387	.580	2.003
3	.387	.290	1.713
4	.418	.200	1.645
5	.469	.150	1.655
6	.567	.439	2.043
7	.467	.510	2.013
8	.407	.419	1.862
9	.292	.414	1.742
10	.292	.333	1.661
11	.292	.413	1.741
12	.292	.435	1.763
13	.292	.360	1.688
14	.292	.388	1.716
15	.292	.482	1.800
16	.292	.403	1.731
17	.292	.410	1.738
18	.292	.473	1.801

* Including 1.036 min. base time.

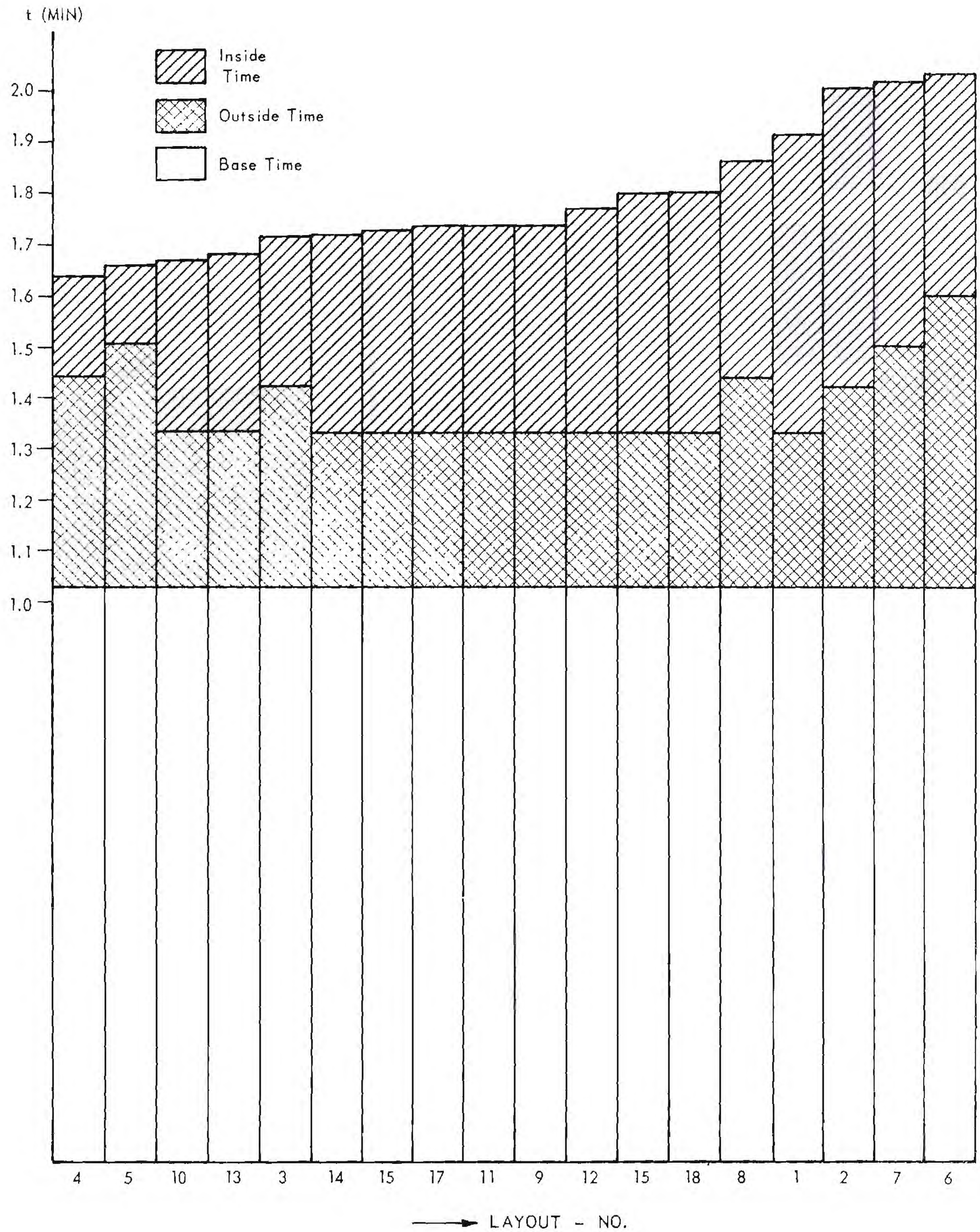


Figure 23. Composition of Handling Times.

The Influence of Warehouse Size on Handling Times

Since these assumed layouts are only examples of very small warehouses, it is important to know how the size of the warehouse influences the handling time.

The three parts into which the total handling time has been divided behave as follows when the size of the storage area is changed:

base time remains constant

outside time remains constant

inside time changes for all layouts with expansion in both directions

For the Layouts 1-5 an increase in size results only in an extension of the longitudinal aisle. It was therefore easy to develop a formula which gives directly t as a function of U.

For the other layouts (6-17) a simple formula could not be developed and the times had to be calculated in the same manner as shown in the previous section. However, since w increases linearly with U, and since t is a linear function of w, the function t = f(U) will also be a linear function.

The values for U = 1000 and 2000 are calculated, the first one merely for control purposes in order to see if the points lie on a straight line with the value for U = 234.

Detailed calculations of the inside time are shown in Appendix C and the results represented in the Figures 24.a and 24.b are obtained by adding the base time and the corresponding outside time.

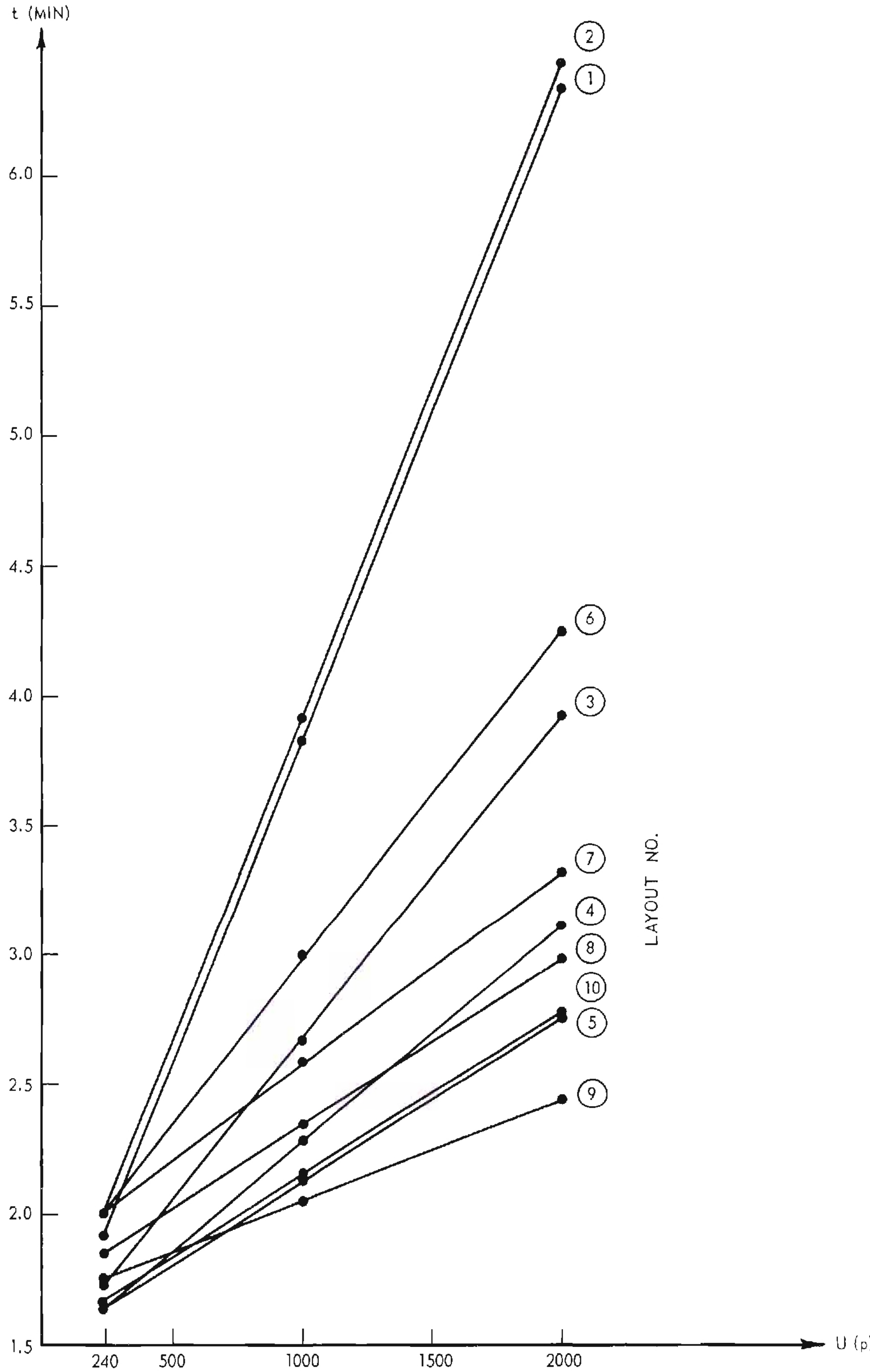


Figure 24a. Total Handling Time as a Function of Size.

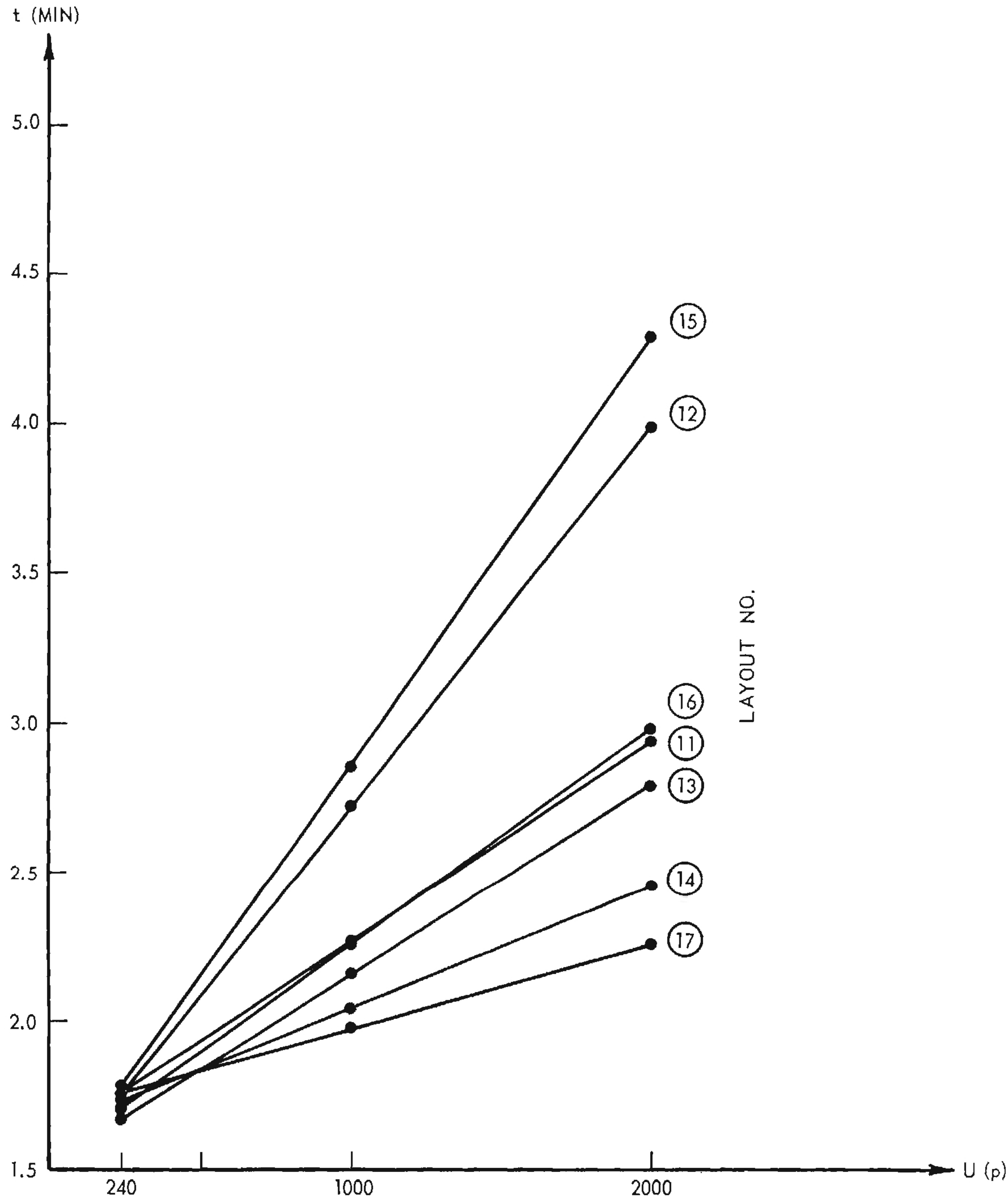


Figure 24b. Total Handling Time as a Function of Size.

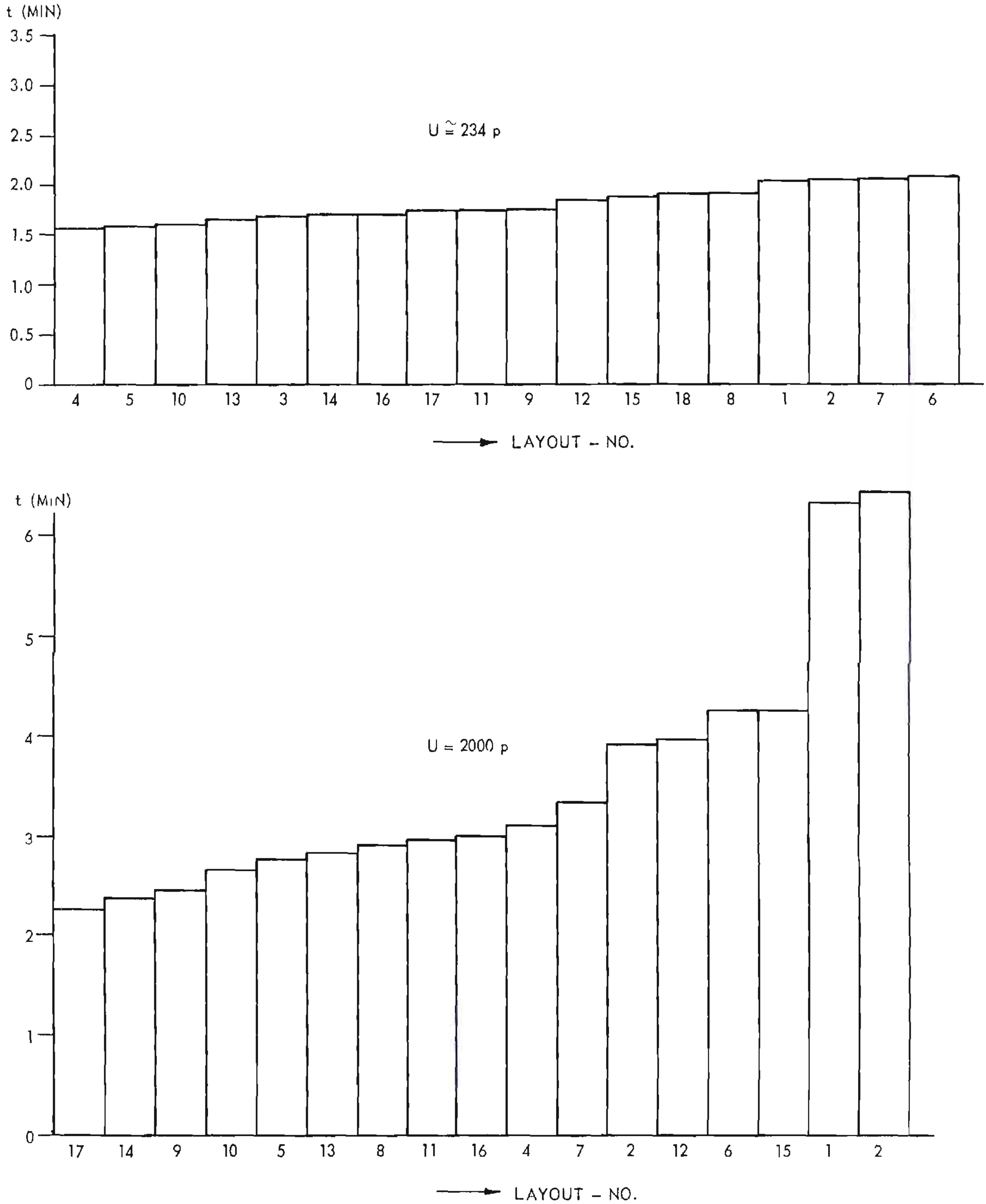


Figure 25. Comparison of Handling Times for Different Sizes and Layouts.

Influence of the Number of Parked Trucks on Handling Times

It has been shown on page 33 that the outside time is considerably less if a truck can be parked directly in front of an entrance. Therefore, if more than one truck is frequently loaded or unloaded at the same time it will be more advantageous to use a layout with several entrances.

It was not possible, however, to develop a simple formula to express the outside time as a function of the number of parked trucks. Therefore, this influence is not investigated any further in this thesis.

CHAPTER IV

THE OPTIMAL SOLUTION

The optimal solution for a given warehouse space requirement and given frequency of handling is that layout that results in the lowest total cost consisting of space costs and handling costs.

The following factors influence the optimal solution:

T : Space requirements (total floor space that is needed to store a given number of pallets, composed of storage space and service space).

C_S : Space costs per pallet (amount that has to be paid yearly for the rent of warehouse space, divided by the number of pallets stored on the floor, or warehouse costs of owned warehouse, also divided by number of stored pallets).

t_H : Average handling time (time in minutes that is needed on the average to pick up one pallet inside the carrier, to transport it to its destination, to store it there and to return to the carrier).

C_H : Handling costs (cost of material handling operation required for the handling of one unit load, composed of direct costs, such as wages and direct truck operation costs and indirect costs, such as depreciation, maintenance, supervision, etc.).

C_T : Total costs = Space costs + handling costs.

F : Frequency of handling (number of turnovers of total stock per year).

Further expressions used in this chapter are:

c_S : Space unit costs (cost of 16 square feet of floor space = 1p).

c_H : Handling unit costs (cost of 1 hour fork truck operation).

The Optimal Solution for the Given Problem

For the 18 layouts given in Chapter II the results are represented in graphical form in Figure 26. The amount of storage space needed to store one pallet is obtained (from Table 1) and the time used to handle one unit load from Table 7.

Even without assigning monetary values to these two factors it can be seen that the Layouts No. 4 and No. 5 are optimal. They combine most efficient storage use with lowest handling times.

The hypothesis that layouts with good space utilization have larger handling times and vice-versa did not turn out to be true. It can be seen that there are layouts (4,5,13) which combine highest space efficiency with lowest handling times and others (2,7) which have lowest space efficiency and highest handling times.

The Influence of Size on the Optimal Solution

If the same diagram as in Figure 26 is drawn for a size of U = 2000p ($T = \frac{1}{E} U_1$, E from Table 5, handling time from Figure 24) it can be seen, that the situation has changed. The best layouts for this size are the numbers 17, 14, and 9. (Figure 27)

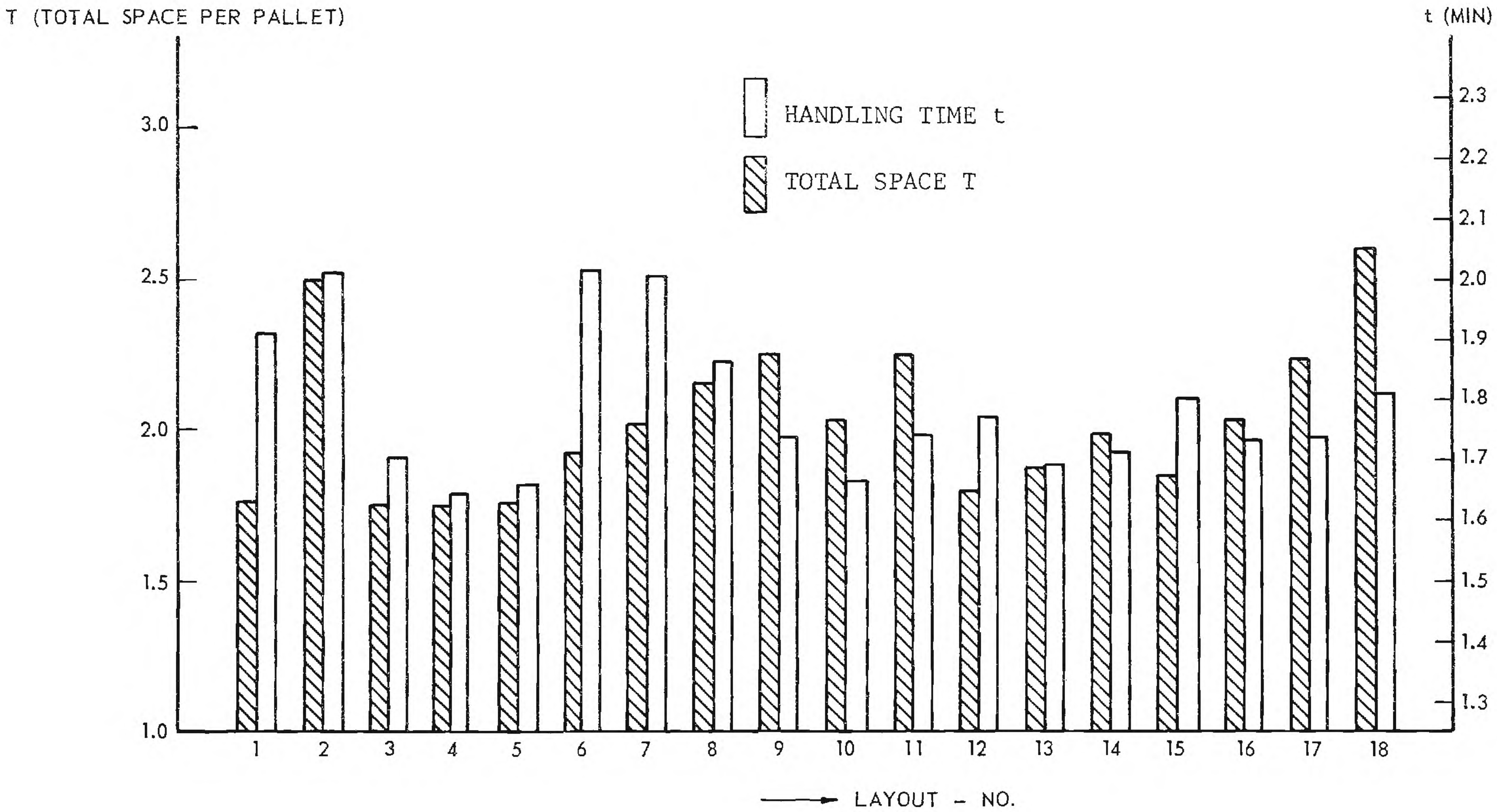


Figure 26. Handling Times and Total Space for the
18 Original Layouts.

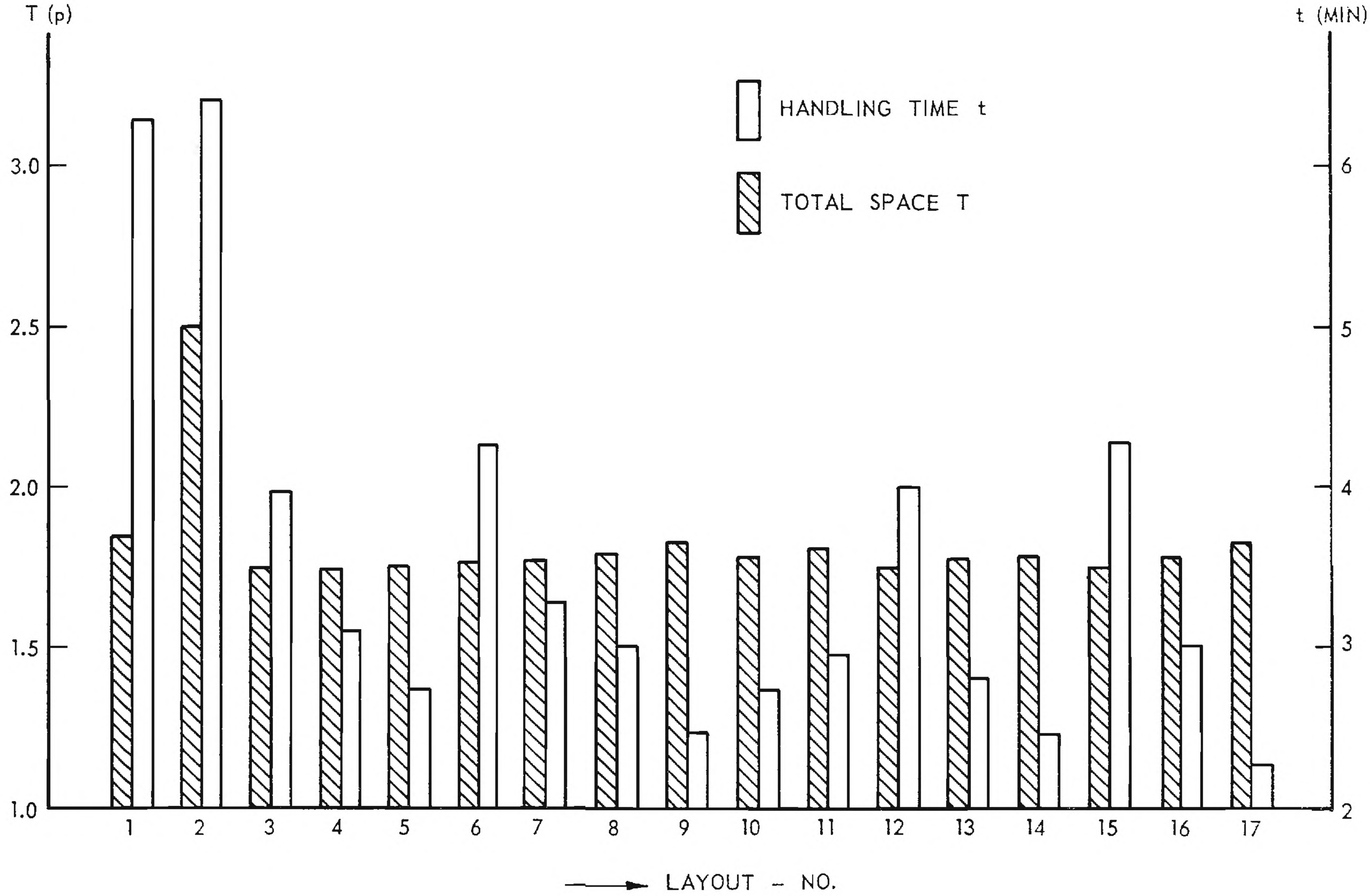


Figure 27. Handling Times and Total Space for U = 2000 p.

Furthermore it can be seen that the space requirements are about the same for all layouts (compare with Figure 21). Therefore the efficiency of the layouts will depend primarily on the handling time required. (An exception is Layout 2.)

As the size of the layout increases, this fact becomes even more significant. As it has been shown in Chapter II, the difference of total space (T) is nearly independent from the size (U) of a layout from a certain size on. However the handling time is a linear function of the size U as it could be shown in Figure 24. Since the increase in handling time is different for each layout, it becomes obvious that for different warehouse sizes the optimal solution may be obtained by different layouts.

If this fact is recognized, the problem that arises is to find which layout represents the best solution for a given size and frequency of handling. This can be done by calculating the total costs for each layout as a function of size. This procedure is shown for two typical cases, No. 1 and No. 9, for the frequency is: F = 10 (Table 8, Figure 28). All other cases could be solved in the same way.

The total costs are calculated in the following way:

The space costs are found by multiplying T with c_s (assumed to be \$16.00).

The handling time t_H is taken from Figure 24.a.

The turnover is equal to U x 3 (stacking height) x F.

c_H is assumed to be \$4.00 per hour = \$0.067 per minute.

The total costs are the sum of space costs and handling costs.

Table 8. Total Handling Costs as a Function of Size for F = 10

LAYOUT NO. 1

U (p)	T (p)	Space Costs C_s ($)	t_H (Minutes)	Unit-Loads (Number)	Handling Time (Minutes)	Handling Costs C_s ($)	Total Costs ($)
200	350	5,600	1.93	6,000	11,590	770	6,370
500	873	14,000	2.59	15,000	38,750	2,580	16,580
1000	1750	28,000	3.83	30,000	115,000	7,650	35,650
1500	2650	42,400	5.09	45,060	228,000	15,220	57,620
2000	3500	56,000	6.33	60,000	380,000	25,300	81,300

LAYOUT NO. 9

U (p)	T (p)	Space Costs C_s ($)	t_H (Minutes)	Unit-Loads (Number)	Handling Time (Minutes)	Handling Costs C_s ($)	Total Costs ($)
200	466	7,480	1.74	6,000	10,220	670	8,150
500	990	15,840	1.87	15,000	28,000	1,870	17,710
1000	1,870	29,920	2.03	30,000	61,000	4,060	33,980
1500	2,760	44,200	2.25	45,000	101,250	6,750	50,950
2000	3,650	58,400	2.45	60,000	146,200	9,770	68,170

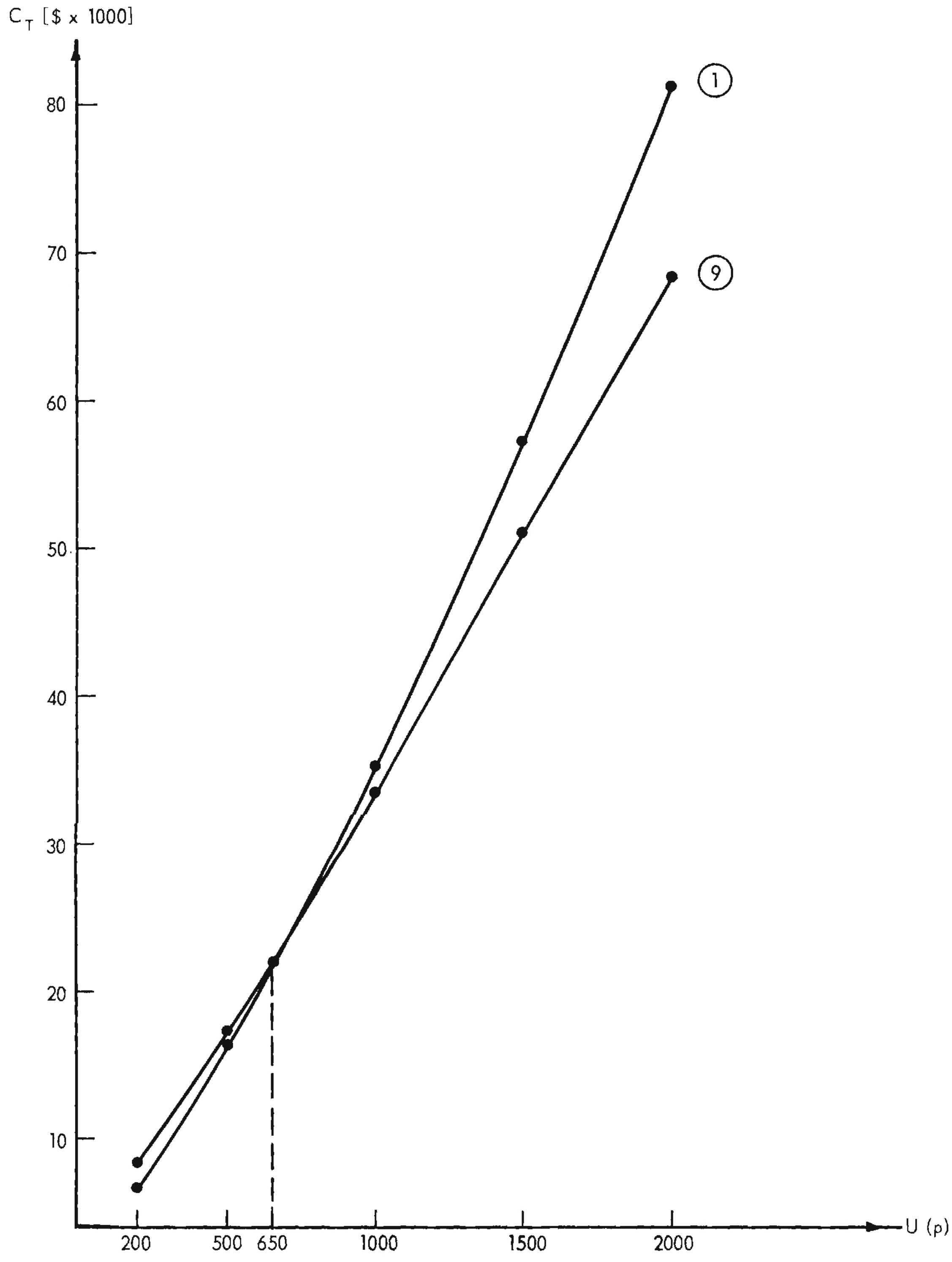


Figure 28. The Influence of Size on Total Costs.

From Figure 28 the following conclusions can be drawn: For an annual turnover of F = 10, a size of 650p is the "critical value," which means that for larger sizes, Layout 9 will be more economical, for smaller sizes, Layout 1.

The Influence of Frequency of Handling on the Optimal Solution

If a warehouse contains very slow moving merchandise, the advantage that it offers due to shorter handling times may be offset by higher space costs. While the problem in the previous section was to find the "critical value of size" for a given frequency of handling, the problem of this section is to find the "critical value of frequency" for a given size, i.e. the frequency at which the total cost of a layout that has larger space requirements but smaller handling times are the same as for another one with low space requirements and high handling times.

Again the Layouts 1 and 9 are selected and the desired frequencies are calculated for U = 234p and U = 2000p.

c_S is assumed \$16.00 per p per year.

c_H is assumed \$4.00 per hour.

(a) U = 234p

Space requirements: (See Table 1)

Layout No. 1	406p
Layout No. 9	525p
Difference in space requirements	-119p
Difference in space costs	-1904 $

Handling Times: (See Table 8)

Layout No. 1	1.908 Minutes
Layout No. 9	1.742 Minutes
Difference in handling times	.166 Minutes
Difference in handling costs	.011 $ Per handling

Layout No. 9 has higher space costs, but offers lower handling times.

How many loads would have to be handled to compensate for the difference in space costs?

$$\frac{\$1904}{\$.011} = 173{,}000 \text{ pallets}$$

What part of the volume represents this number?

$$\frac{173{,}000}{3 \times 234} = 246.40$$

This result shows that with an annual turnover 246.40 times both cases are equal in costs. For higher turnovers, Layout No. 9 is more economical because the higher space costs are offset by lower handling costs. Figure 29 represents this finding graphically. The handling costs are obtained by the following formula:

$$\frac{t_H \times 234 \times 3}{60} \times \$4.00 \times F$$

and the space costs by multiplying T with \$16.00.

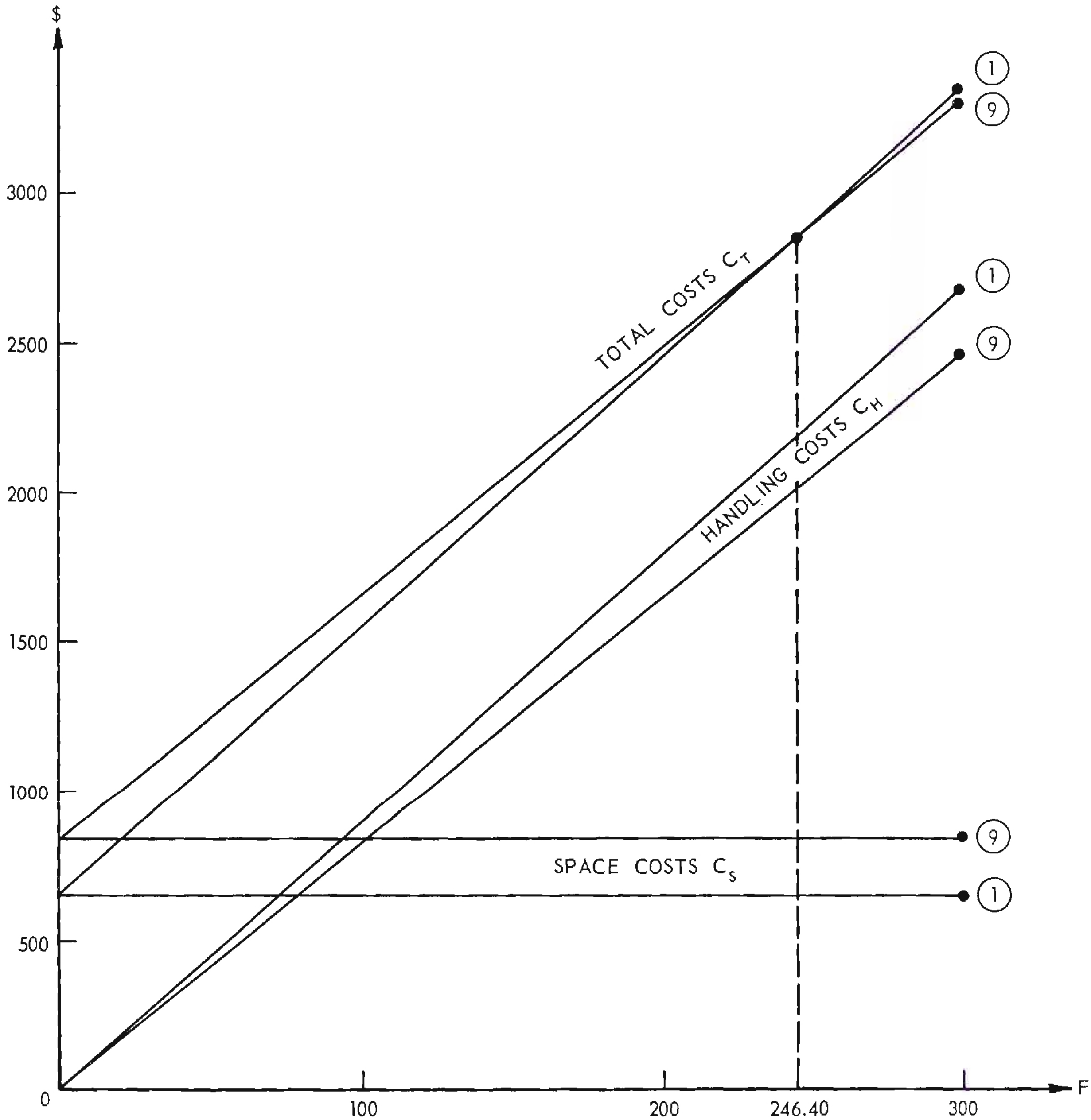


Figure 29. The Influence of Frequency of Handling on the Optimal Solution.

(b) U = 2000p

Space requirements: (= U $\frac{1}{E}$, from Table 5)

Layout No. 1	3500p
Layout No. 9	3620p
Difference in space requirements	-120 p
Difference in space costs	-1920$

Handling times: (See Figure 24.a)

Layout No. 1	6.33 Minutes
Layout No. 9	2.44 Minutes
Difference in handling time	3.89 Minutes
Difference in handling costs	0.259 Per handling

How many loads would have to be handled to compensate for the difference in space costs?

$$\frac{\$1920}{\$.259} = 7,420 \text{ pallets}$$

What part of the volume represents this number?

$$\frac{7,420}{3 \times 2000} = 1.236$$

This result shows that with an annual turnover of 1.236 times, both cases are equal in costs. For higher turnovers, Layout No. 9 is more economical. The result could also be represented graphically as in Figure 29.

The Influence of Unit Costs on the Optimal Solution

It was mentioned in the introduction that the optimal solution may be influenced considerably by the unit costs. As Figure 26 shows this will not be the case for the assumed layouts of size U = 234p because there are solutions which result in minimal space and handling costs regardless of unit costs.

The situation is similar for large warehouses (U = 2000p) where the difference in space requirements between layouts becomes very small. But it would still be interesting to find to what degree the unit costs influence the optimal solution. This can be found in answering the two following questions: (Layouts No.9 and No. 10 are considered.)

(a) What difference in handling unit costs would cause Layout No. 9 and No. 10 to have equal total costs, using the same space unit costs?

(b) What difference in space unit costs would cause Layout No. 9 and No. 10 to have equal total costs, using the same handling unit costs?

F is assumed to be = 10.

(a) c_s is assumed to be $16.00 per p per year.

Space requirements:

Layout No. 9	3620p
Layout No. 10	3580p
Difference in space requirements	40p
Difference in space costs	640$

Handling times:

Layout No. 10	2.78 min.
Layout No. 9	2.44 min.
Difference in handling time	.34 min. per handling

Number of pallets handled per year: U x 3 x F

$$= 2000 \times 3 \times 10 = 60{,}000$$

Total difference in handling time: $\frac{.34 \times 60{,}000}{60} = 340$ hours

This results means that Layout No. 10 requires 340 hours more handling time, but $640 less space costs than No. 9.

How large would the handling unit costs have to be in order to compensate for the higher space costs?

$$\frac{\$160}{340 \text{ Hours}} = \$1.88/\text{hour}$$

The assumed unit handling costs were $4.00 per hour. $\frac{\$4.00}{\$1.88} = 2.125.$ The handling costs would have to be 2.125 times smaller or 0.47 times the original cost in order to result in equal costs for both layouts. For even lower handling costs, Layout No. 10 would be more economical because of lower space costs. Figure 30 shows the graphical solution.

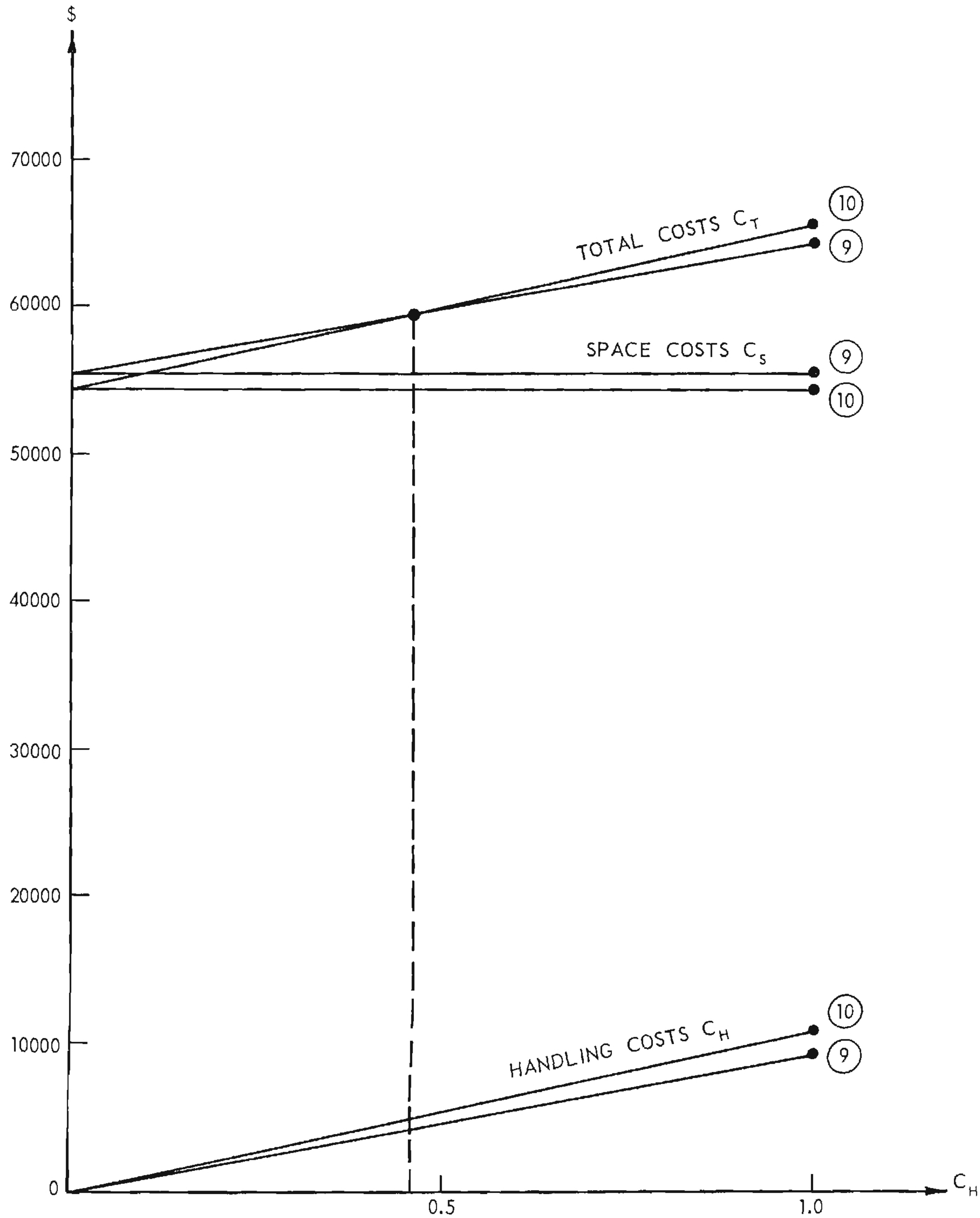


Figure 30. The Influence of Handling Unit Costs on the Optimal Solution.

(b) c_H is assumed to be $4.00 per hour.

Difference in handling time 340 hrs (see previous page).

Difference in handling costs: 340 hrs x $4.00 = $1360

Difference in space requirements: 40 p (see previous page).

$$\frac{1360}{40p} = \$34/p$$

The assumed unit space costs were $16.00 per p. $\frac{\$34}{\$16} = 2.125$.

The space unit costs would have to be 2.125 times larger in order to result in equal costs for both layouts. For higher space costs, Layout No. 10 would be more economical.

As the calculations show, Layout No. 9 is more economical by $1,360 - $160 = $1,200 because of the shorter handling times. In order to make Layout No. 10 more economical, the space costs would have to be increased by more than 2.125 times, or the handling costs decreased by more than 2.125 times.

The graphical solution of this problem would look similar to Figure 30.

CHAPTER V

DISCUSSION

1. Space Efficiency

As could be expected, the difference between the 18 layouts in space efficiency is considerable for the given size (U = 234p) and varies from 38.5 per cent to 57.2 per cent. As a result, the space requirements also vary considerably as can be seen from Figure 19. However, the fact that the difference in space efficiency levels off at about 56 per cent with increasing size (Figure 21) seems to be surprising at first. It is more easily understood if it is realized that the extension of the warehouse is made only by increasing the length of the aisles and keeping the number of aisles constant. As a result the ratio of storage space to service space necessarily increases.

The space efficiency for a given layout can be improved by increasing the stacking depth. The increase in efficiency is relatively less noticeable as the pallet depth increases. Figure 20 shows this fact graphically. An increase in stacking depth from one to two pallets gives a gain in efficiency of about 15 per cent, from five to six, however, of only 3 per cent.

Another interesting fact is that the absolute difference in total space requirements remains nearly constant as the size of the layout is increased. This is shown in Figure 22 for the Layouts

No. 9 and No. 12. Highest space efficiency is achieved when the number of aisles is minimal (Nos. 1,12,15) and when no aisle intersections exist (Nos. 3,4,5).

2. Handling Times

Figure 25 shows that the handling times do not differ very much for the 18 representative layouts with the size of U = 234p. However, the difference is considerable for larger sizes, i.e., 1000p and up. The lowest handling times are found for layouts with approximately square shape and with several entrances (Nos. 4,5, and 10). Highest handling times exist for layouts where added area is mainly in one direction (Nos. 1,2,7,6). If long transverse aisles exist, an entrance in the middle is to be preferred to an entrance on each end (Nos. 12,13,14).

3. The Optimal Solution

The hypothesis that layouts with good space utilization have higher handling times and vice-versa did not turn out to be true. As can be seen from Figure 26, there are layouts (Nos. 4,5,13) which combine highest space efficiency with lowest handling times and others (No. 2,7) which have lowest space efficiency and highest handling times.

Figure 27 shows that the optimal solution depends considerably on the size of the warehouse. While the differences in space requirements have decreased, those of handling times have increased. Since the space efficiency has become less pronounced, the optimal solution will be found among layouts with lowest handling times (Nos. 17,14,9).

Figure 28 shows how the size can influence the selection of the optimal layout by means of the two examples Layout No. 1 and No. 9. While for small sizes No. 9 results in higher total costs, there exists a size above which No. 1 becomes more expensive. This size, here called "critical size," is the value at which the cost curves of the two layouts intersect. It is a function of the frequency of handling.

The influence of the frequency of handling on the selection of the optimal solution is investigated in Chapter IV with Layouts No. 1 and No. 9. It is proven that even for these cases where the handling times differ considerably, the frequency of handling can be neglected for small warehouses (i.e. U = 234p), however, must be considered for larger ones (i.e. U = 2000p). For U = 234p, the annual turnover would have to be more than 246 times in order to favor Layout No. 9 over No. 1. For U = 2000p, however, the annual turnover would only have to be 1.236 or larger in order to reverse the selection.

The unit costs, too, influence the optimal solution. The given example (Layouts No. 9 and No. 10) shows that with fixed space costs, the handling costs would have to be $\frac{1}{2.125}$ times as large or about 0.47 times the original assumed value in order to affect the selection. With handling costs fixed, the space costs would have to be 2.125 times larger.

CHAPTER VI

CONCLUSIONS

The following conclusions can be drawn from this thesis:

1. The space efficiency can be expressed mathematically as a function of size and stacking depth for any given type of layout. It is influenced mainly by the stacking depth. While for small warehouses the type of layout has a great influence on space efficiency, it can almost be neglected for larger ones.

2. The average handling times can be calculated for different types of layouts by using standard times. However, these calculations require a considerable amount of work and are not very practical to carry out. It is not possible to express handling times mathematically as a function of size for the same type of layout. Yet, it was found that these times increase linearly with increasing size. Warehouses with several entrances offer the advantage of having shorter "outside" times, but the influence on the total times is not very great.

3. The size of a warehouse influences the selection of the optimal layout and has to be taken into consideration.

4. For small warehouses (less than 1000p) there exist layouts which combine highest space efficiency with lowest handling times. For larger warehouses, however, the best solutions are the ones which result in lowest handling times, since the difference in space efficiency becomes very small.

5. When selecting a layout for a small warehouse (less than 1000 pallets) the frequency of handling can be neglected, since the difference in handling times is not very great. For larger warehouses, however, it can influence the selection.

6. Handling and space unit costs both influence the selection of the optimal solution to the same degree. However, in most cases the influence of handling costs can be neglected, since the variation is usually small. The space unit costs, on the other hand vary considerably for different locations and different warehouse types and should always be considered.

CHAPTER VII

RECOMMENDATIONS

In this study several factors that influence the selection of the best layout have not been taken into consideration, as the scope of this study did not permit the inclusion of too many details.

It would be interesting to study how the system of "storage according to popularity" influences the handling times for different layouts. The writer briefly investigated this factor for the original 18 layouts, but was not able to determine the influence of the size on the handling times and for that reason abandoned that phase of the project. When investigating this field, the fact that the popularity may change during the year according to seasonal influences, should be considered.

A similar study to the one presented here could also be undertaken for warehouses that do not use the principle of palletized unit loads and where the material handling is not done by fork trucks.

Since this work represents mainly a theoretical investigation of the problem, it is suggested that a study be undertaken to find practical solutions, i.e., to show what type of warehouse layout should be selected for given capacity, space unit costs, handling unit costs and frequency of handling. Since the necessary calculation will be very time consuming, it is suggested that it be carried out on a computer. The results should be represented in graphical or tabular form which will be suitable for practical use.

APPENDIX A

DETAILED CALCULATION OF THE TIME ELEMENTS

1. Calculation of Base Time

The base time is composed of two parts: The time spent inside the carrier and the actual storage operation in the warehouse. The following operations take place inside the carrier:

Operation:	Distance:		Time: (Minutes)
Hoist up	48"	(e)	.135
Run in, 2nd level		(e)	.080
Tilt backward		(e)	.025
Run out		(1)	.060
Hoist down	48"	(1)	.086
			.385

(e) empty (1) loaded

The following operations take place inside the warehouse:

Operation:	Distance:		Time: (Minutes)	
Turn left and stop, forward		(1)	.060	.067
Turn right and stop, forward		(1)	.075	
Hoist up	48"	(1)		.159
Run in 2nd level		(1)		.100
Tilt forward				.025
Run out		(e)		.060
Hoist down	48"	(e)		.144
Turn left and stop, reverse		(e)	.065	.065
Turn right and stop, reverse		(e)	.065	
Accelerate		(e)		.030
				.650

Total base time: .385

.650

1.035 Minutes

2. Calculation of the Outside Time for the Two Different Situations Shown on Pages 33 and 34.

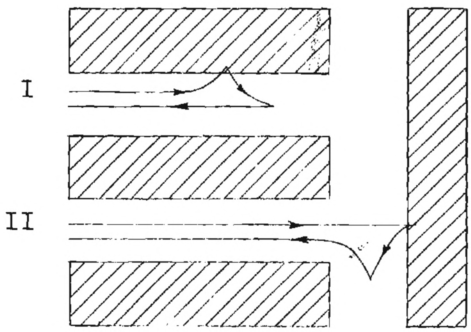
Case I:	Move in		.066
	Move out		.066
	Turn left and stop, reverse		.080
	Turn right forward		.055
	Accelerate		.025
			.292 Minutes
Case II:	Turn left, forward	(e)	.055
	Turn right, forward	(e)	.055
	Move in		.066
	Move out		.066
	Turn left and stop, reverse		.080
	Accelerate		.025
	Turn right, forward	(1)	.055
			.402 Minutes

(add .010 min. per pl distance d)

An objection could be made to simply adding the different time elements because certain operations can be performed concurrently (e.g., "hoist down" and "turn left, reverse"). The developer of the data, when asked about this fact did admit such a possibility, however recommended against considering it. Even though a skilled operator is able to reduce the handling time in such a way, the time obtained by adding time elements will be appropriate for the average operator (see letter from Yale & Towne Manufacturing Company in Appendix E).

Further Conventions Concerning the Calculation of Times

1. The Difference in Stacking Time Along the Aisle and in Front of the Aisle



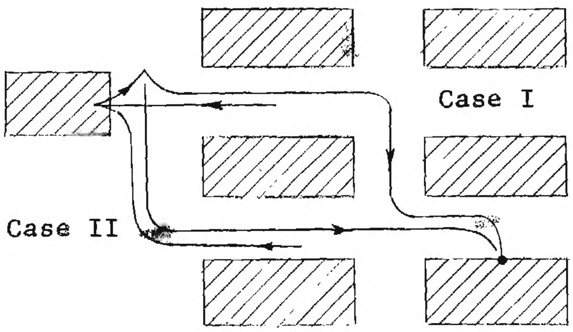
Case I: Time in warehouse as calculated on page 67: .650 minutes

Case II: Actual stacking operation without turns (see page 67)

The following elements are subtracted:			.650
Turn and stop, forward	(1)	(average)	.067
Turn and stop, reverse	(e)	(average)	.065
			.518
The following elements are added instead			
Turn right and stop	(e)	reverse	.065
Turn left	(e)	forward	.055
			.638 Minutes

The time difference between these two cases is therefore .012 minutes. As it can be seen from the figures 1-18, the time of Case II can be used for maximal 5 per cent of the storage area. For a precise calculation therefore, 5 per cent of .012 minutes = .0006 minutes should be subtracted from all average times. Since all times are carried only to three decimals, this does not influence the average times, and all calculations can be made using the values of Case I.

2. In some cases a point in the warehouse can be reached in different ways:



The time used for these two possibilities can be calculated as follows: (Since the straight distance travelled is the same, the time used for it has not to be taken into consideration).

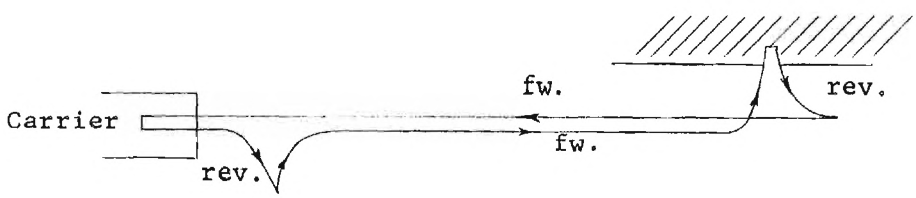
Case I:	Time I from page 68	.292
	2 turns	.110
		.402 Minutes
Case II:	Time II from page 68	.402 Minutes

The results show that the times used are the same for Case I and Case II. Since the way in Case II goes along the ramp it is more subjected to be influenced by other fork trucks. Therefore the Case I is preferred and used in all further calculations. From this fact follows that for a number of cases where different entrances as well as transversal aisles exist, the outside time of Case I can be used instead of the time found by the formula on page 34.

Another great advantage of this method is that the outside time becomes independent of the size, a fact that turns out to be very practical in further calculations.

3. There are two basic methods by which a fork truck may be driven:

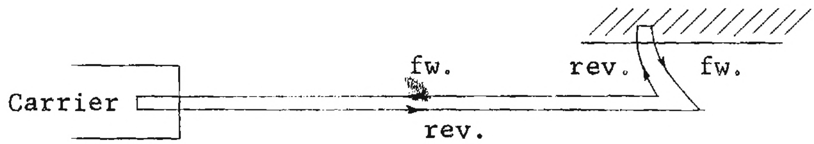
Method I: Both directions forward



Time:	"Outside" time	.292
	Turn left, forward	.055
	Turn left and stop, reverse	.080
	Accelerate	.025
		.452 Minutes

(Plus time for straight run)

Method II: One direction forward, one direction backward



Time:	Move in and out of truck	.132
	Stop	.036
	Turn right, forward	.055
	Turn left and stop, reverse	.080
		.303 Minutes

(Plus time for straight run)

The standard times given for straight run lead to the conclusion that the speed for straight movement forward and backward are the same. However, it can be doubted if this will really be true in the long-run. It is obvious that the driver becomes more tired when he has to drive backwards and this will certainly result in an increase of general handling time.

For this reason only Method I is used in all calculations.

APPENDIX B

THE CALCULATION OF THE AVERAGE INSIDE TIMES

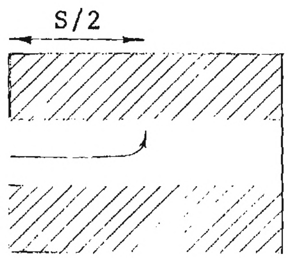
The inside time has been defined as the time that is used to travel from the entrance of the storage area to the location of storage and back to the entrance.

<u>Layouts No. 1, 2, 3, 4 and 5:</u>

For these layouts the average length of way will be to the middle of the aisle and back to the entrance which is equivalent to the length of the aisle. The average inside time is therefore the time needed to travel this distance.

The standard time is 0.0025 minutes per foot or 0.0100 minutes per pl (pallet length).

The following sketch explains this procedure:



$$\text{Time} = 2 \times \frac{s}{2} \times 0.01 \text{ min} = h \times 0.01 \text{ [min]}$$

The following results have been found:

Layout Number	s (pl)	Time (Minutes)
1	58	.580
2	58	.580
3	29	.290
4	20	.200
5	15	.150

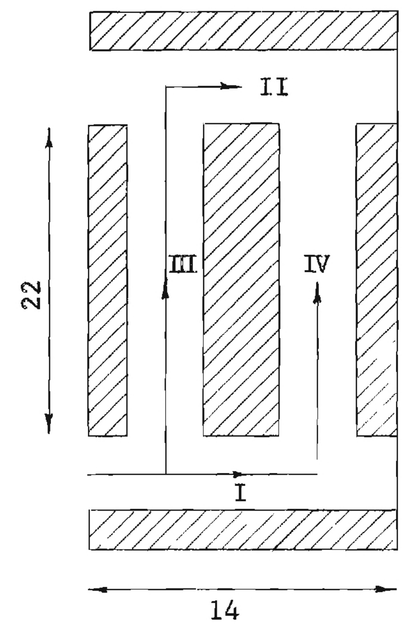
Layouts No. 6-18

For these layouts the calculation of the average time is more complicated. The principle is the following: The storage area that is served from one aisle is designated by a Roman numeral. The time required to reach the center of this area is calculated and then multiplied by the percentage this area represents of the total area. The average time is then the sum of these products.

The time that is used for turns is added (0.055 min. per turn).

For each layout a sketch is given which explains the calculations and on which the dimensions and the percentages are indicated.

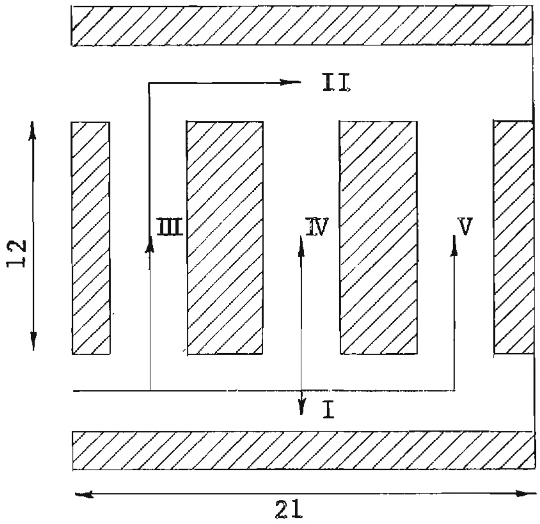
Layout No. 6



Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(7)	14		.140	12	.168
II	2(2 + 22 + 2)	52		.520		
			4	.220		
				.740	12	.89
III	2(2 + 11)	26		.260		
			2	.110		
				.370	38	.141
IV	2(9 + 11)	40		.400		
			2	.110		
				.510	38	.192
					100	.4388

$\bar{t}$ = .439 Minutes

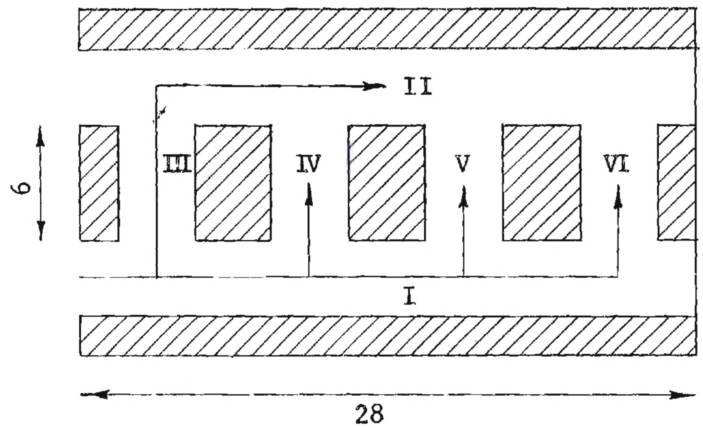
Layout No. 7



Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(10.5)	21		.210	18.4	.0386
II	2(2 + 12 + 5.5)	39		.390		
			4	.220		
				.610	18.4	.1191
III	2(2 + 6)	16		.160		
			2	.110		
				.270	21.1	.057
IV	2(9 + 6)	30		.300		
			2	.110		
				.410	21.1	.0865
V	2(16 + 6)	44		.880		
			2	.110		
				.990	21.1	.209
					100.1	.5102

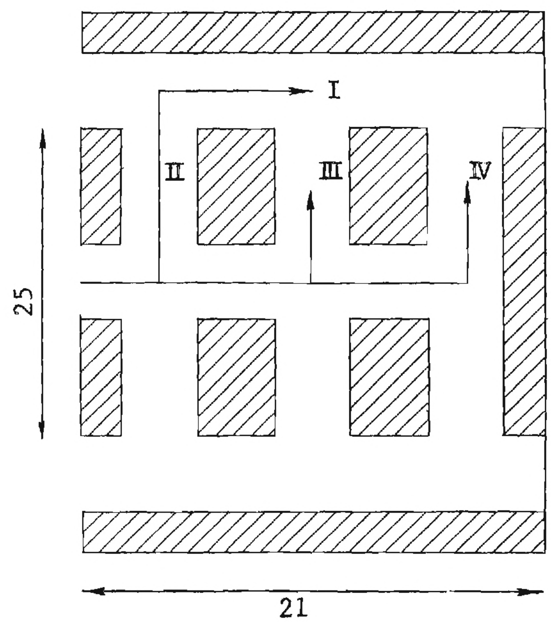
$\bar{t} = .510$

Layout No. 8



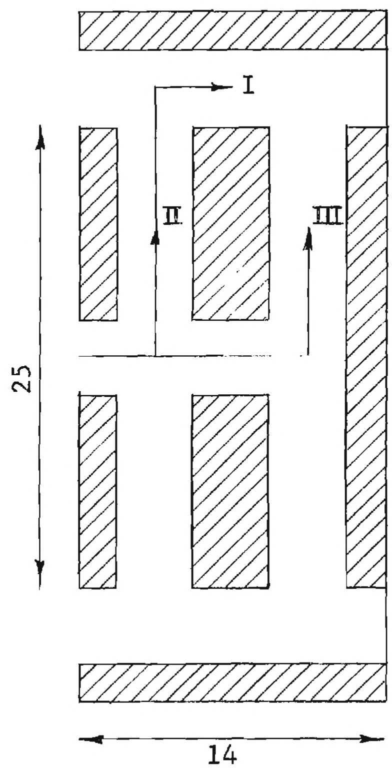
Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(14)	28		.280	27	.0755
II	2(2 + 6 + 9)	34		.340		
			4	.220		
				.560	27	.1520
III	2(2 + 3)	10		.100		
			2	.110		
				.210	11.5	.0241
IV	2(9 + 3)	24		.240		
			2	.110		
				.350	11.5	.0402
V	2(16 + 3)	38		.380		
			2	.110		
				.490	11.5	.0562
VI	2(23 + 3)	52		.520		
			2	.110		
				.630	11.5	.0723
		$\bar{t}$ = .419 Minutes			100	.4193

Layout No. 9



Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(2 + 6 + 5.5)	27		.270		
			4	.220		
				.490	35.8	.1752
II	2(2 + 3)	10		.100		
			2	.110		
				.210	21.4	.0476
III	2(9 + 3)	24		.240		
			2	.110		
				.350	21.4	.0796
IV	2(16 + 3)	38		.380		
			2	.110		
				.490	21.4	.1116
		$\bar{t}$ = .414 Minutes			100	.4140

Layout No. 10



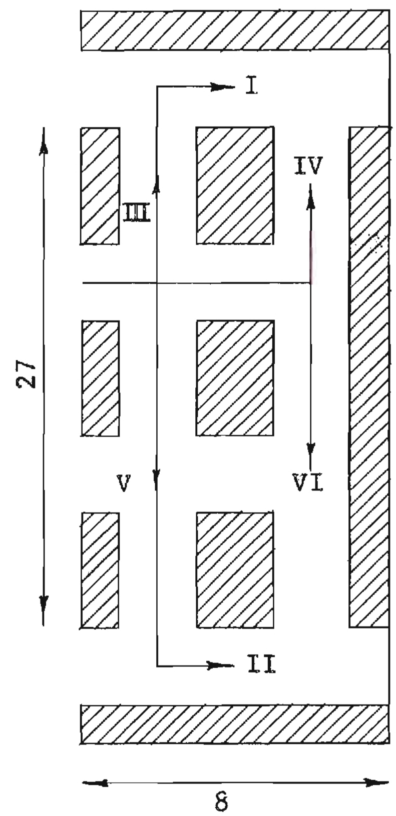
Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(2 + 11 + 4)	34		.340		
			4	.220		
				.560	35.9	.1860
II	2(2 + 5.5)	15		.150		
			2	.110		
				.260	32.1	.0574
III	2(9 + 5.5)	29		.290		
			2	.110		
				.400	32.1	.0884
		$\bar{t}$ = .333 Minutes			100.1	.3328

Layout No. 11

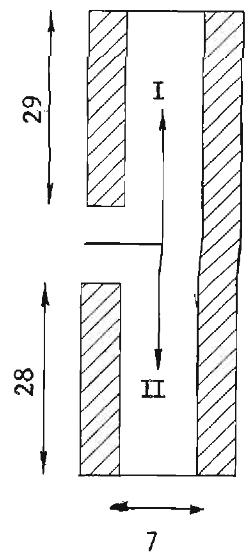
(Sketch on Next Page)

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(2 + 7 + 2)	22		.220		
			4	.220		
				.440	11.85	.0520
II	2(2 + 18 + 2)	44		.440		
			4	.220		
				.660	11.85	.0785
III	2(2 + 3.5)	11		.110		
			2	.110		
				.220	12.7	.0280
IV	2(9 + 3.5)	25		.250		
			2	.110		
				.360	12.7	.0460
V	2(2 + 9.5)	23		.230		
			2	.110		
				.340	25.4	.0860
VI	2(9 + 9.5)	37		.370		
			2	.110		
				.480	25.4	.1220
		$\bar{t}$ = .413 Minutes			99.9	.4125

Layout No. 11



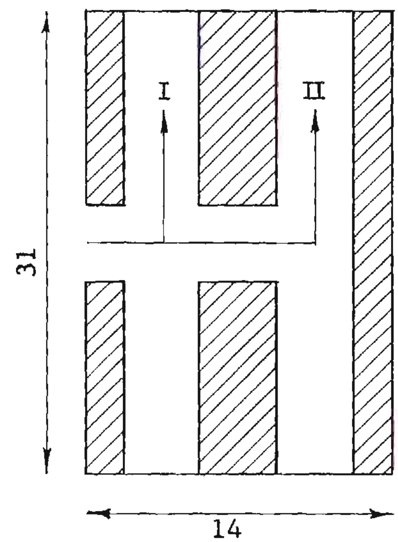
Layout No. 12



Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(2 + 14.5)	33		.330		
			2	.110		
				.440	51.7	.2075
II	2(2 + 14)	32		.320		
			2	.110		
				.430	48.3	.227
					100	.4345

$\bar{t}$ = 0.435 Minutes

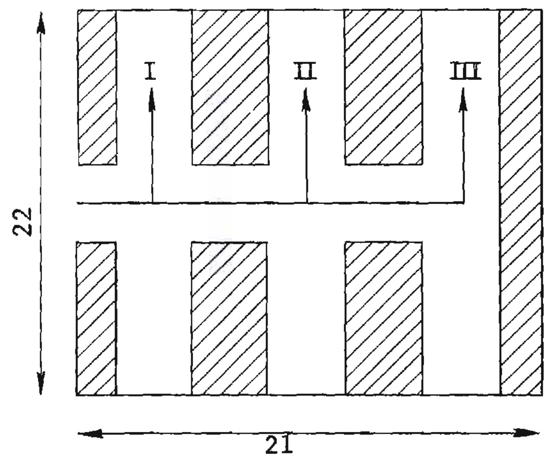
Layout No. 13



Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(2 + 7)	18		.180		
			2	.110		
				.290	50	.1450
II	2(9 + 7)	32		.320		
			2	.110		
				.430	50	.2150
					100	.3600

$\bar{t}$ = .360 Minutes

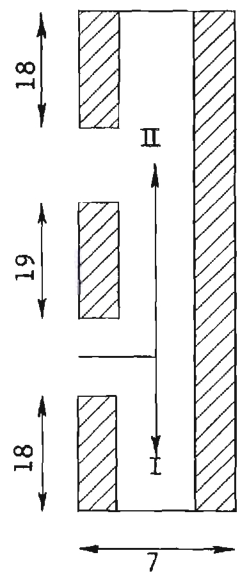
Layout No. 14



Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(2 + 5)	14		.140		
			2	.110		
				.250	33.3	.0822
II	2(9 + 5)	28		.280		
			2	.110		
				.390	33.3	.1300
III	2(16 + 5)	42		.420		
			2	.110		
				.530	33.3	.1760
					100	.3882

$\bar{t}$ = .388 Minutes

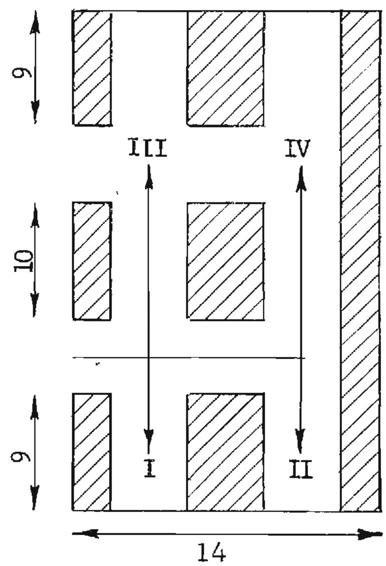
Layout No. 15



Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(2 + 9)	22		.220		
			2	.110		
				.330	33.3	.1100
II	2(2 + 205)	45		.450		
			2	.110		
				.560	66.6	.3720
					99.9	.4820

$\bar{t}$ = .482 Minutes

Layout No. 16



Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(2 + 4.5)	13		.130		
			2	.110		
				.240	16.6	.0398
II	2(9 + 4.5)	27		.270		
			2	.110		
				.380	16.6	.0630
III	2(2 + 11.5)	27		.270		
			2	.110		
				.380	33.3	.1265
IV	2(9 + 11.5)	41		.410		
			2	.110		
				.520	33.3	.1740
					99.8	.4033

$\bar{t}$ = .403 Minutes

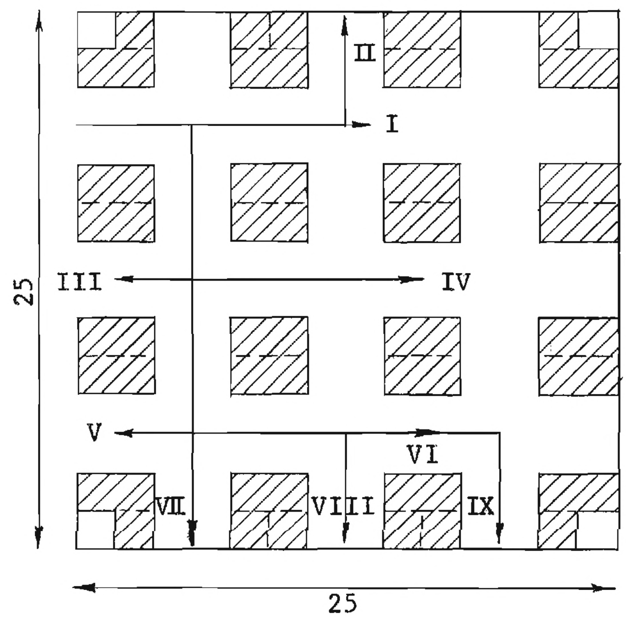
Layout No. 17

(Sketch on Next Page)

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(2 + 3)	10		.100		
			2	.110		
				.210	11.1	.0233
II	2(9 + 3)	24		.240		
			2	.110		
				.350	11.1	.0388
III	2(16 + 3)	38		.380		
			2	.110		
				.490	11.1	.0545
IV	2(2 + 7.5)	19		.190		
			2	.110		
				.300	22.2	.0668
V	2(9 + 7.5)	33		.330		
			2	.110		
				.440	22.2	.0980
VI	2(16 + 7.5)	47		.470		
			2	.110		
				.580	22.2	.1290
					99.9	.4104

$\bar{t} = .410$

Layout No. 18



Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(12.5)	25		.250	26.6	.0668
II	2(11 + 2)	26		.260		
			2	.110		
				.370	10.0	.0370
III	2(4 + 4 + 1)	18		.180		
			4	.220		
				.420	6.4	.0268
VI	2(4 + 4 + 9)	17		.170		
			4	.220		
				.390	20.2	.0788
				Carry Over	63.2	.2094

Layout No. 18 (Continued)

Storage Area	Length of Way (pl)	Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
				Carry Over	63.2	.2094
V	2(4 + 11 + 5)	40		.400		
			4	.220		
				.620	6.4	.0396
VI	2(4 + 11 + 9)	48		.480		
			4	.220		
				.700	20.2	.1414
VII	2(4 + 18)	44		.440		
			2	.220		
				.660	3.3	.0218
VIII	2(4 + 18 + 4)	52		.520		
			6	.330		
				.850	3.3	.0280
IX	2(4 + 18 + 11)	66		.660		
			6	.330		
				.990	3.3	.0326
					99.4	.4728

$\bar{t}$ = .473 Minutes

APPENDIX C

THE CALCULATION OF THE INSIDE TIMES AS A FUNCTION OF SIZE

Layouts No. 1-5:

For these layouts the calculation is relatively simple. The only variable is the length of the longitudinal aisle which can easily be expressed as a function of U. The inside time is consequently:

$= s \times 0.01(\text{min})$ (s in pl, 0.01 min is the time used to travel 1 pl).

The calculations are shown on the next page.

Layouts No. 6-17:

These calculations are carried out very similar to those in Appendix B. In all these layouts only the transversal aisle is expanded and therefore only the value of w (length of transversal aisle) changes. This value can be found as a function of U according to the formulas given in Table 4.

Only the calculations for U = 2000 p are shown here. The values for U = 1000 p have also been calculated but merely to check the linearity of the function t = f(U).

Layouts No. 1-5

Layout No.	Size U (p)	s f(U)	h (pl)	t (Minutes)	Fixed Time (Base Time + Outside T.) (Minutes)	Total Time
1	1000	$\frac{U}{4}$	250	2.500	1.328	3.828
	2000		500	5.000	1.328	6.328
2	1000	$\frac{U}{4}$	250	2.500	1.423	3.923
	2000		500	5.000	1.423	6.423
3	1000	$\frac{U}{8}$	125	1.250	1.423	2.673
	2000		250	2.500	1.423	3.923
4	1000	$\frac{U}{12}$	83.3	0.833	1.454	2.287
	2000		166.6	1.666	1.454	3.120
5	1000	$\frac{U}{16}$	62.5	0.625	1.505	2.130
	2000		125	1.250	1.505	2.755

Layout No. 7

$$w = \frac{U - 84}{12} = 159$$

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(10.5)	21		.210	2.1	.0044
II	2(2 + w + 5.5)	166		1.660		
			4	.220		
				1.880	2.1	.0395
III	$2(2 + \frac{w}{2})$	163		1.630		
			2	.110		
				1.740	31.9	.5582
IV	$2(9 + \frac{w}{2})$	177		1.770		
			2	.110		
				1.880	31.9	.5980
V	$2(16 + \frac{w}{2})$	191		1.910		
			2	.110		
				2.020	31.9	.6440
					100	1.8441

$$\bar{t} = 1.844$$

Layout No. 8

$$w = \frac{U - 112}{16} = 118$$

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(14)	28		.280	5.6	.0154
II	2(2 + w + 9)	258	4	2.580 .220 2.800	5.6	.1540
III	$2(2 + \frac{w}{2})$	122	2	1.220 .110 1.330	22.2	.2950
IV	$2(9 + \frac{w}{2})$	136	2	1.360 .110 1.470	22.2	.3260
V	$2(16 + \frac{w}{2})$	150	2	1.500 .110 1.610	22.2	.3570
VI	$2(23 + \frac{w}{2})$	164	2	1.640 .110 1.750	22.2	.3880
					100	1.5354

$$\bar{t} = 1.535$$

Layout No. 9

$$w = \frac{U - 90}{12} + 3 = 162$$

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	$2(2 + \frac{w - 3}{2} + 5.5)$	174	4	1.740 .220 1.960	4.2	.0822
II	$2(2 + \frac{w - 3}{4})$	83.5	2	.835 .110 .945	31.9	.3010
III	$2(9 + \frac{w - 3}{4})$	97.5	2	.975 .110 1.085	31.9	.3460
IV	$2(16 + \frac{w - 3}{4})$	115	2	1.115 .110 1.225	31.9	.3900
					99.9	1.1190

$$\bar{t} = 1.119$$

Layout No. 6

$$w = \frac{U - 52}{8} = 243$$

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	2(7)	14		.140	1.4	.0019
II	2(2 + w + 2)	494		4.940		
			4	.220		
				5.160	1.4	.0720
III	$2(2 + \frac{w}{2} + 2)$	247		2.470		
			2	.110		
				2.580	48.6	1.2600
IV	$2(9 + \frac{w}{2})$	261		2.610		
			2	.110		
				2.720	48.6	1.3220
					100	2.6562

$\bar{t}$ = 2.656 Minutes

Layout No. 10

$$w = \frac{U - 62}{8} + 3 = 245.1$$

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	$2(2 + \frac{w - 3}{2} + 4)$	254.9		2.549		
			4	.220		
				2.769	2.8	.0774
II	$2(2 + \frac{w - 3}{4})$	124.6		1.246		
			2	.110		
				1.356	48.6	.6530
III	$2(9 + \frac{w - 3}{4})$	138.6		1.386		
			2	.110		
				1.496	48.6	.7230
					100	1.4534

$$\bar{t} = 1.453$$

Layout No. 11

$$w = \frac{U - 68}{8} + 6 = 248$$

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	$2(2 + \frac{w - 6}{3} + 2)$	169.2	4	1.692 .220 1.712	1.4	.0268
II	$2(2 + 2\frac{w - 6}{3})$	332.4	4	3.324 .220 3.544	1.4	.0495
III	$2(2 + \frac{w - 6}{6})$	84.6	2	.846 .110 .956	16.2	.1550
IV	$2(9 + \frac{w - 6}{6})$	98.6	2	.986 .110 1.096	16.2	.1870
V	$2(2 + \frac{w - 6}{6} + 6)$	171.8	2	1.718 .110 1.828	32.4	.5830
VI	$2(9 + \frac{w - 6}{6} + 6)$	185.8	2	1.858 .110 1.968	32.4	.6039
					100	1.6058

$$\bar{t} = 1.606 \text{ Minutes}$$

Layout No. 12

$$w = \frac{U + 6}{4} = 501.5$$

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	$2(2 + \frac{w - 3}{4})$	253.7		2.537		
			2	.110		
				2.647	50	1.324
II	$2(4 + \frac{w - 3}{2})$	253.7		2.537		
			2	.110		
				2.647	50	1.323
					100	2.647

$$\bar{t} = 2.647 \text{ Minutes}$$

Layout No. 13

$$w = \frac{U + 18}{8} = 252.2$$

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	$2(2 + \frac{w - 3}{4})$	130		1.300		
			2	.110		
				1.410	50	.7050
II	$2(9 + \frac{w - 3}{4})$	144		1.440		
			2	.110		
				1.550	50	.7525
					100	1.4575

$\bar{t}$ = 1.458 Minutes

Layout No. 14

$$w = \frac{U + 30}{12} = 169.5$$

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	$2(2 + \frac{w - 3}{4})$	86.8		.868		
			2	.110		
				.978	33.3	.3260
II	$2(9 + \frac{w - 3}{4})$	100.8		1.008		
			2	.110		
				1.118	33.3	.3706
III	$2(16 + \frac{w - 3}{4})$	114.8		1.148		
			2	.110		
				1.258	33.3	.4160
					99.9	1.1126

$$\bar{t} = 1.113 \text{ Minutes}$$

Layout No. 15

$$w = \frac{U + 12}{4} = 503$$

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	$2(2 + \frac{w - 6}{6})$	200		2.000		
			2	.110		
				2.110	33.3	.7000
II	$2(2 + 2\frac{w - 6}{6} + 6)$	390		3.390		
			2	.110		
				3.500	66.6	2.3300
					99.9	3.0300

$\bar{t}$ = 3.030 Minutes

Layout No. 16

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	$2(2 + \frac{w - 6}{6})$	86	2	.860 .110 .970	16.6	1.6200
II	$2(9 + \frac{w - 6}{6})$	100	2	1.000 .110 1.110	16.6	1.8600
III	$2(2 + \frac{w - 6}{3} + 3)$	171	2	1.710 .110 1.820	33.3	6.0700
IV	$2(9 + \frac{w - 6}{3} + 3)$	205	2	2.050 .110 2.160	33.3	7.2000
					99.8	16.7500

$\bar{t}$ = 1.675 Minutes

Layout No. 17

$$w = \frac{U + 60}{12} = 172$$

Storage Area	Length of Way (pl)	Total Length (pl)	Turns (Number)	Time (Minutes)	%	Time (Minutes)
I	$2(2 + \frac{w - 6}{6})$					
II	$2(9 + \frac{w - 6}{6})$	73.3	2	.733 .110 .843	33.3	.28000
III	$2(16 + \frac{w - 6}{6})$					
IV	$2(2 + \frac{w - 6}{6} + 1.5)$					
V	$2(9 + \frac{w - 6}{6} + 1.5)$	76.3	2	.763 .110 .873	66.6	.58000
VI	$2(2 + \frac{w - 6}{6} + 1.5)$					
					99.9	.86000

$\bar{t}$ = 0.860 Minutes

APPENDIX D

How to Measure Fork Truck Performance

	BASIC MOTIONS		DESCRIPTION	TRUCK: YALE K51 AT 40 TIME IN MINUTES Empty	1,000 lbs.	2,000 lbs.	3,000 lbs.	4,000 lbs.
STRAIGHT RUNS	1. FORWARD	Per Foot	Begins when the truck has reached full speed at the end of acceleration, ends when a truck begins to stop.	.0023	.0024	.0025	.0025	.0027
	2. REVERSE	"		.0023	.0024	.0025	.0025	.0027
	3. ACCELERATE	Per Occurrence	Occurs each time the truck moves from dead stop to full speed.	.030	.025	.025	.025	.025
	4. STOP	"	Includes application of brakes to bring truck to dead stop from full speed.	.020	.033	.034	.035	.036
	5. RUN-IN, 1st LEVEL	"	Covers moving the truck at slow speed from a dead stop to insert the forks into a pallet, or to place a pallet (after the forks have been raised). The time value includes starting and stopping. The horizontal distance through which the truck moves is approximately 4 feet, the length of the pallet. 1st level is ground level; 2nd level is 4 feet and 3rd is 8 feet above ground level.	.080	.080	.080	.070	.070
	6. RUN-IN, 2nd LEVEL	"		.080	.090	.110	.100	.100
	7. RUN-IN, 3rd LEVEL	"		.110	.120	.130	.120	.120
	8. RUN-OUT, 1st LEVEL	"	Covers withdrawal of forks from a pallet or removing a pallet, includes starting and stopping. The truck moves backward approximately 4 feet when performing this motion. Levels are the same as for "run-in"	.060	.065	.065	.060	.060
	9. RUN-OUT, 2nd LEVEL	"		.060	.065	.070	.060	.060
	10. RUN-OUT, 3rd LEVEL	"		.060	.070	.070	.080	.080
TURNS	11. RIGHT, FORWARD	"	A change of direction to the right, usually 90 degrees and in the minimum turning radius, while the truck is running forward (11) or backward (12).	.055	.055	.055	.055	.055
	12. RIGHT, REVERSE	"		.055	.055	.055	.055	.055
	13. RIGHT AND STOP, FORWARD	"	Same as motions 11 and 12, except that the truck comes to a dead stop at the end of the turn. This motion is usually followed by "hoist" or "run-in"	.070	.070	.070	.075	.075
	14. RIGHT AND STOP, REVERSE	"		.065	.085	.080	.080	.080
	15. LEFT, FORWARD	"	Same as motions 11 through 14, except turns are made to the left instead of right.	.055	.055	.055	.055	.055
	16. LEFT, REVERSE	"		.055	.055	.055	.055	.055
	17. LEFT AND STOP, FORWARD	"		.060	.060	.060	.060	.060
	18. LEFT AND STOP, REVERSE	"		.065	.075	.075	.065	.070
STACKING	19. TILT	"	Tilt the fork carriage forward or backward.	.025	.025	.025	.025	.025
	20. HOIST UP	Per Inch	Move the fork carriage up, while the truck is at rest.	.0028	.0029	.0030	.0032	.0033
	21. HOIST DOWN	"	Reverse of motion 20.	.0030	.0018	.0018	.0018	.0018

BASIC MOTIONS are the necessary fork truck operating elements that determine the normal minimum amount of time required to perform a materials handling operation. They're easy to identify and measure from a simple operation layout plan. **TIME STANDARDS** for the basic motions make it possible to calculate operating time—even before the job is done.

APPENDIX E

THE YALE & TOWNE MANUFACTURING COMPANY

Yale Materials Handling Division

11,000 ROOSEVELT BOULEVARD

PHILADELPHIA 15, PENNSYLVANIA

ORchard 3-1200

November 15, 1963

Mr. Jurg B. Hemmi
Box 30438
Georgia Tech
Atlanta 13, Georgia

Dear Mr. Hemmi:

Your letter of November 9th was referred to my attention, for the opinion you requested.

We agree with Professor Apple that a number of operations can be performed simultaneously, by a skilled fork truck operator.

However, we believe that the measurement of fork truck operations should be based on an average fork truck operator, working in a safe manner.

We strongly recommend that you continue the practice of adding the different time elements.

On this basis, the data can be defended, if necessary, in the case of any discussions with labor representatives, who would logically argue in terms of 'average operator' and 'safety conditions'.

In almost all industrial work, a skilled employee can improve upon the standard method established for the average employee.

We are enclosing a copy of our Work Kit for application of Standard Performance Data for Fork Lift Trucks.

Sincerely,

Bruno A. Moski

Bruno A. Moski
Manufacturing Administrator

BAM:mhl

Encl.

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